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BOUT Simulations of Edge Turbulence in the DIII-D Tokamak

Bruce I. Cohen, Maxim Umansky, William Nevins, and Mike Makowski
Lawrence Livermore National Laboratory
Livermore, CA 94551

Jose Boedo, Dmitry Rudakov, and Chris Holland, UC San Diego, San Diego, CA

George McKee and Zheng Yan
University of Wisconsin-Madison, Madison, Wisconsin

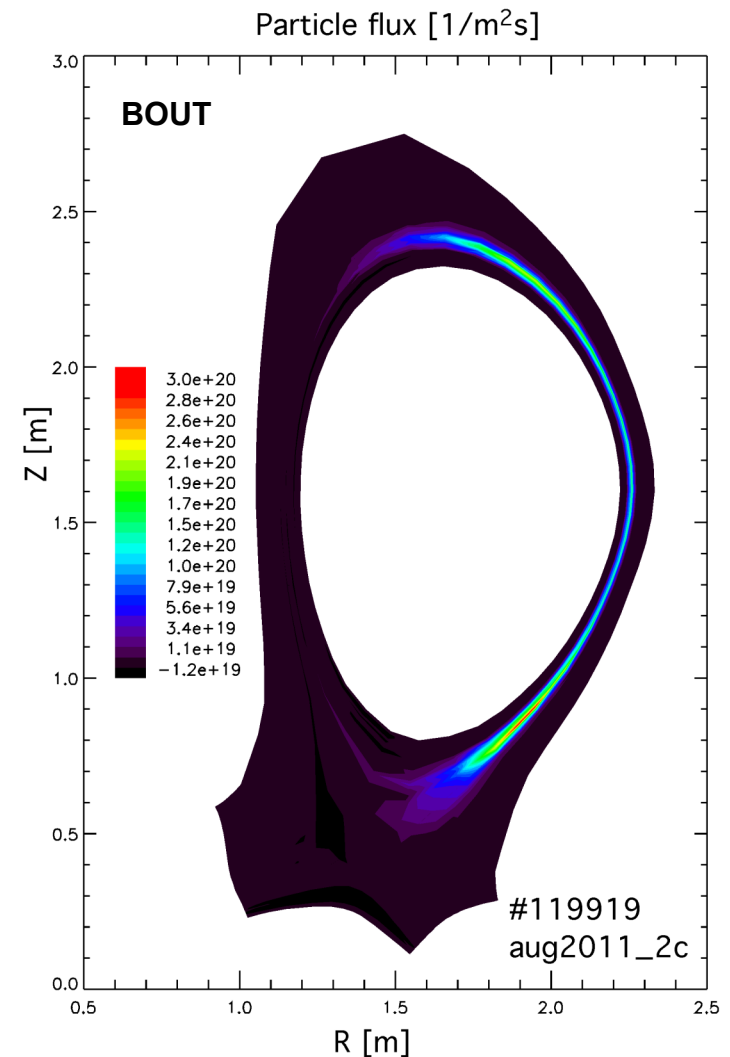
DIII-D Collaboration, General Atomics
La Jolla, CA



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BOUT Simulations of Resistive Ballooning Turbulence in Edge Region for DIII-D Shot #119919

- Simulations of electrostatic resistive ballooning in DIII-D shot #119919/119921, with full geometry and magnetic shear, crossing the separatrix
- Nonlinear BOUT equations for ion density, vorticity, electron and ion velocities, Ohm's law, and Maxwell's equations.
- In earlier work, we have suppressed a spatial odd-even mode ballooning along the field line by either filtering with ∇_{\parallel}^2 or $-\nabla_{\parallel}^4$ diffusive operator added to right side of vorticity and ion density eqns, or with use of a staggered mesh for ∇_{\parallel} representation. Parallel damping included here; no odd-even mode seen.
- **Simulation results with/without T_e fluctuations**
- **BOUT obtains steady-state turbulence with fluctuation amplitudes and transport that compare reasonably to the DIII-D data.**



BOUT Simulation of Resistive Ballooning Turbulence for DIII-D Shot #119919 - Outline

- BOUT algorithmic issues -- control of an odd-even numerical contamination
- Electromagnetic simulations of resistive ballooning turbulence in single-null DIII-D geometry:
 - Case #1: No T_e fluctuations
 - Case #2: With T_e fluctuations
 - Case #3: With T_e fluctuations and electron parallel thermal conduction
 - Case #4: With T_e fluctuations, electron parallel thermal conduction, and $\nabla_{\parallel} = \mathbf{b}_0 \cdot \nabla + \tilde{\mathbf{b}} \cdot \nabla$ in the vorticity eqn.
- Comparison to probe data for DIII-D shot #119919. Shot #119919 is a well-characterized L-mode shot exhibiting steady-state turbulence.

BOUT06 produces expected ballooning-like turbulence in full DIII-D X-point geometry

- BOUT solves Braginskii-like fluid equations for fluid turbulence in various geometries

$$\frac{\partial N_i}{\partial t} + (V_E + V_{\parallel}) \cdot \nabla N_i = \left(\frac{2c}{eB} \right) b_0 \times \kappa \cdot (\nabla P_e - N_i e \nabla \phi) + \nabla_{\parallel} (j_{\parallel} / e) - N_i \nabla_{\parallel} V_{\parallel i}$$

$$\frac{\partial \varpi}{\partial t} + V_E \cdot \nabla \varpi = 2\omega_{ci} b_0 \times \kappa \cdot \nabla P + N_i Z_i e \frac{4\pi V_A^2}{c^2} \nabla_{\parallel} j_{\parallel} \quad \text{vorticity}$$

$$\frac{\partial V_{\parallel e}}{\partial t} = -\frac{e}{m_e} E_{\parallel} - \frac{1}{Nm_e} (T_e \nabla_{\parallel} N_i) + 0.51 \nu_{ei} j_{\parallel}$$

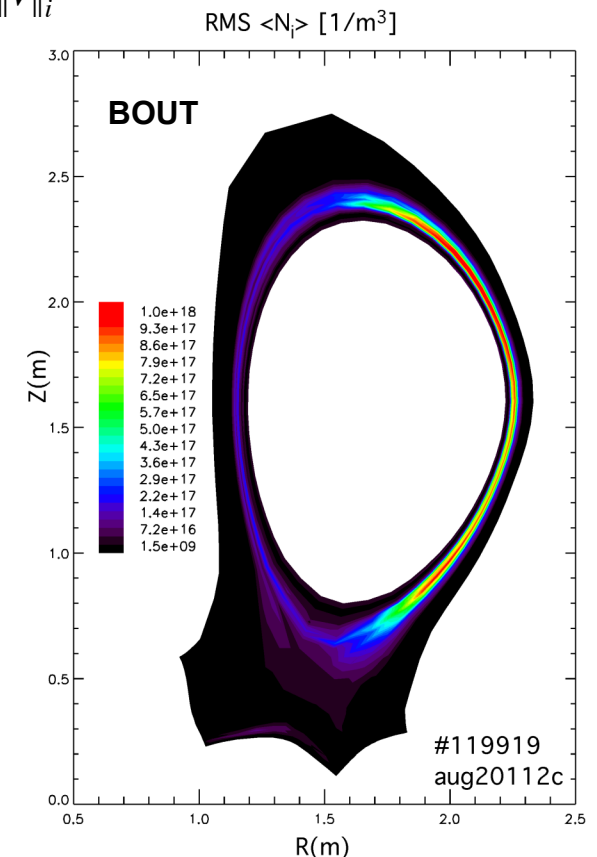
$$\frac{\partial V_{\parallel i}}{\partial t} + V_E \cdot \nabla V_{\parallel i} = -\frac{1}{N_i M_i} \nabla_{\parallel} P$$

$$\mathbf{E} = -\frac{1}{c} \frac{\partial}{\partial t} \mathbf{A}_{\parallel} - \nabla \phi, \quad -\nabla_{\perp}^2 \mathbf{A}_{\parallel} = \frac{4\pi}{c} \mathbf{j}_{\parallel}, \quad \mathbf{B} = \nabla \times \mathbf{A}_{\parallel} + \mathbf{B}_0$$

$$\varpi = \nabla \cdot (e Z_i N_i \nabla \phi) \approx e Z_i N_i \nabla^2 \phi \quad \nabla_{\parallel} \approx \mathbf{b}_0 \cdot \nabla$$

- Electromagnetic with $\nabla_{\parallel} \approx \mathbf{b}_0 \cdot \nabla$
- Finite-difference equations
- Implicit time integration with PVODE
- Quasi-ballooning with zero-gradient radial bdy conditions

Distribution of $\langle \delta N_i \rangle$ in saturated turbulence



Resistive Ballooning Simulations with BOUT -- Odd-even Numerical Mode Can Be Controlled with Normalized Diffusive Damping in Poloidal Angle

- Control the odd-even mode with $\partial/\partial t \rightarrow \partial/\partial t + \nu^*(k_\theta)$ in the vorticity and ion density eqns with diffusion operator in poloidal angle and normalized coeff.:

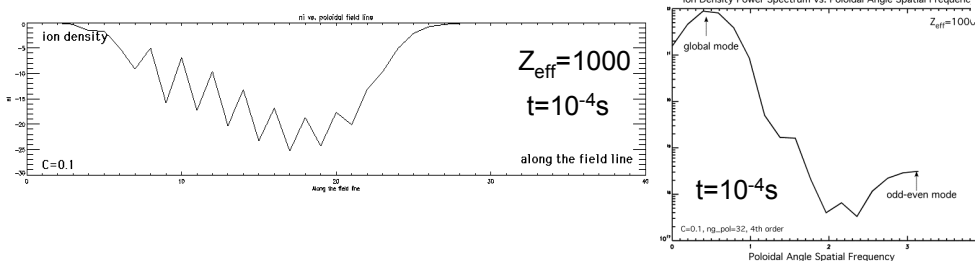
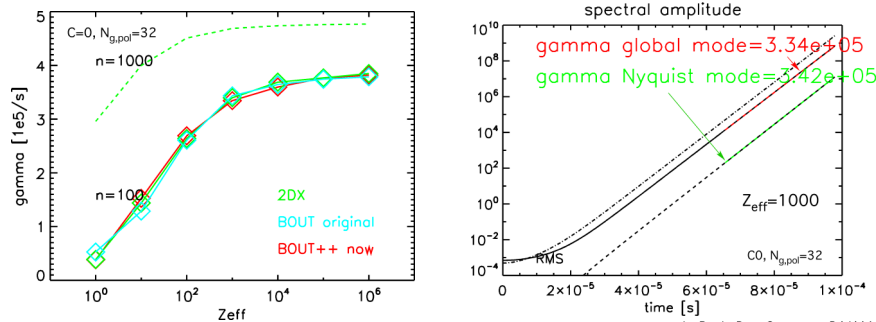
$$\nu^*(k_\theta) = \frac{C}{\Delta t} \left\{ -(\Delta\theta/2)^2 D_\theta^2, (\Delta\theta/2)^4 D_\theta^4 \right\} \rightarrow \frac{C}{\Delta t} \left\{ \sin(k_\theta \Delta\theta/2)^2, \sin(k_\theta \Delta\theta/2)^4 \right\}$$

- Damping of the odd-even mode is proportional to normalized coefficient C

C=0

$n_{g,pol}=32$ 4th order

Odd-even mode evident

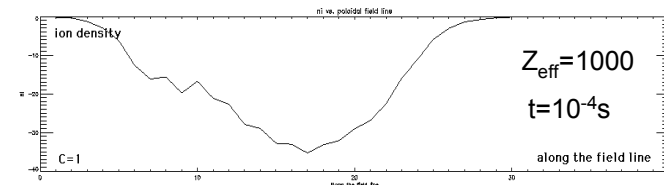
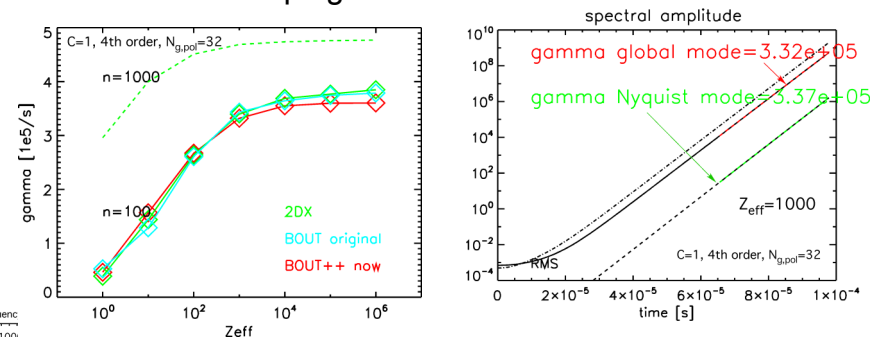


$$A(\text{Nyquist})/A(\text{global}) \sim (\Delta x_\parallel)^3 (\Delta x_\parallel/2L_\parallel)^n, \quad n=2,4$$

C=1

$n_{g,pol}=32$ 4th order

Damping of odd-even mode



- Note: Staggered grid for ∇_\parallel representation resolves problem with ∇_\parallel^2 finite-difference stencil & also removes odd-even mode

Case #1: BOUT06 produces expected drift-resistive ballooning turbulence in full DIII-D X-point geometry

- Consider the following simplified equation set in the BOUT06 framework:

$$\frac{\partial N_i}{\partial t} + (V_E + V_{\parallel}) \cdot \nabla N_i = \left(\frac{2c}{eB} \right) b_0 \times \kappa \cdot (\nabla P_e - N_i e \nabla \phi) + \nabla_{\parallel} (j_{\parallel} / e) - N_i \nabla_{\parallel} V_{\parallel i}$$

$$\frac{\partial \varpi}{\partial t} + V_E \cdot \nabla \varpi = 2\omega_{ci} b_0 \times \kappa \cdot \nabla P + N_i Z_i e \frac{4\pi V_A^2}{c^2} \nabla_{\parallel} j_{\parallel}$$

$$\frac{\partial V_{\parallel e}}{\partial t} = -\frac{e}{m_e} E_{\parallel} - \frac{1}{Nm_e} (T_e \nabla_{\parallel} N_i) + 0.51 \nu_{ei} j_{\parallel}$$

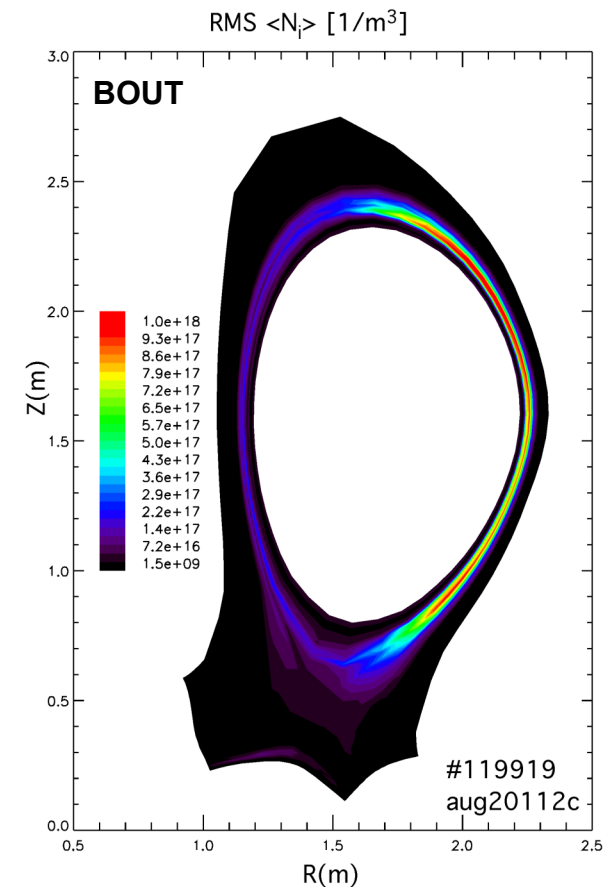
$$\frac{\partial V_{\parallel i}}{\partial t} + V_E \cdot \nabla V_{\parallel i} = -\frac{1}{N_i M_i} \nabla_{\parallel} P$$

$$\mathbf{E} = -\frac{1}{c} \frac{\partial}{\partial t} \mathbf{A}_{\parallel} - \nabla \phi, \quad -\nabla_{\perp}^2 \mathbf{A}_{\parallel} = \frac{4\pi}{c} \mathbf{j}_{\parallel}, \quad \mathbf{B} = \nabla \times \mathbf{A}_{\parallel} + \mathbf{B}_0$$

$$\varpi = \nabla \cdot (e Z_i N_i \nabla \phi) \approx e Z_i N_i \nabla^2 \phi \quad \nabla_{\parallel} \approx \mathbf{b}_0 \cdot \nabla$$

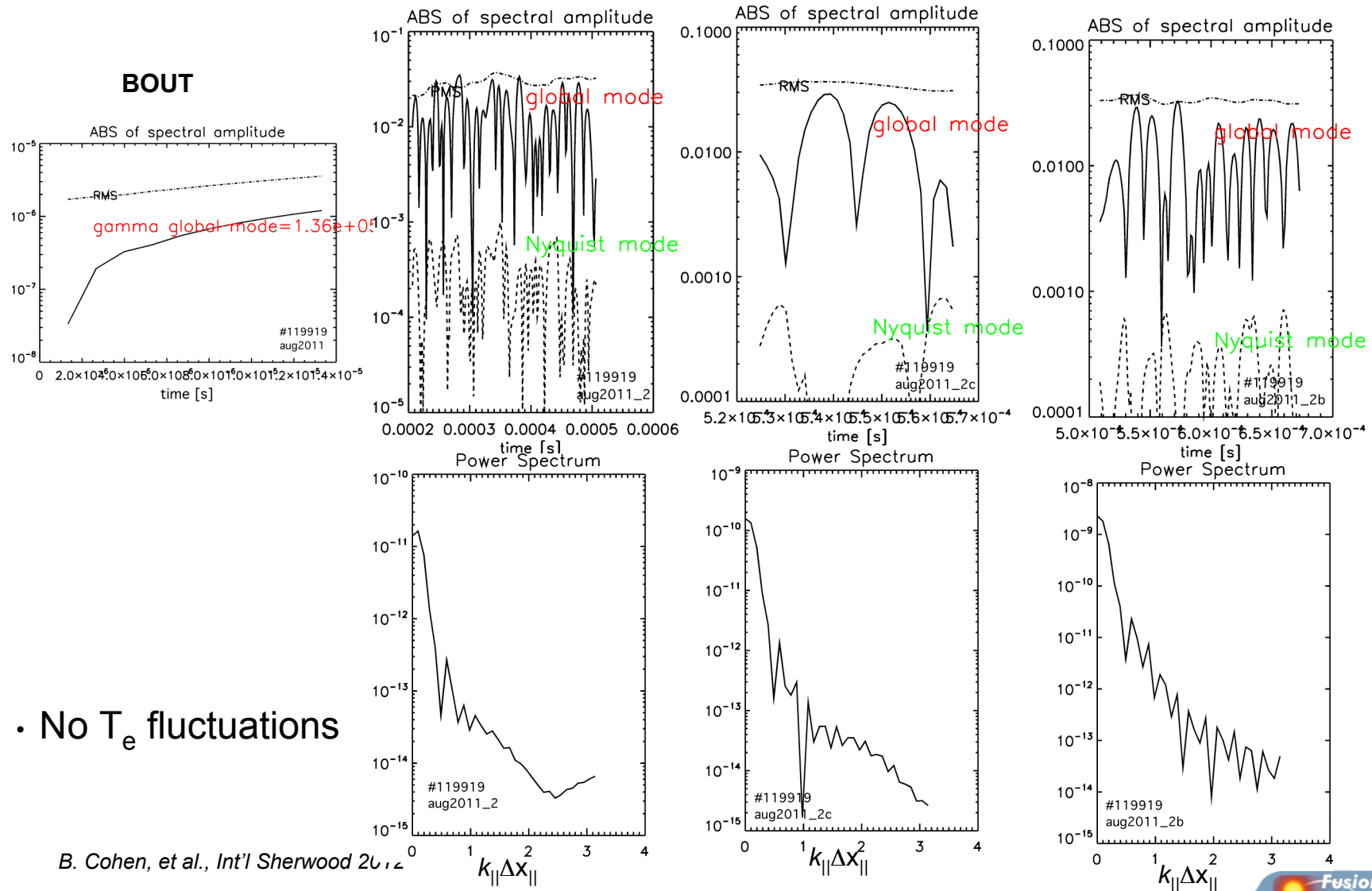
- Electromagnetic with $\nabla_{\parallel} \approx \mathbf{b}_0 \cdot \nabla$
- Actual DIII-D geometry
- DIII-D - like fixed background profiles for shot 119919
- No T_e fluctuations

**Distribution of $\langle \delta N_i \rangle$
in saturated turbulence**



BOUT-06 produces saturated turbulence for DIII-D geometry with no T_e fluctuations

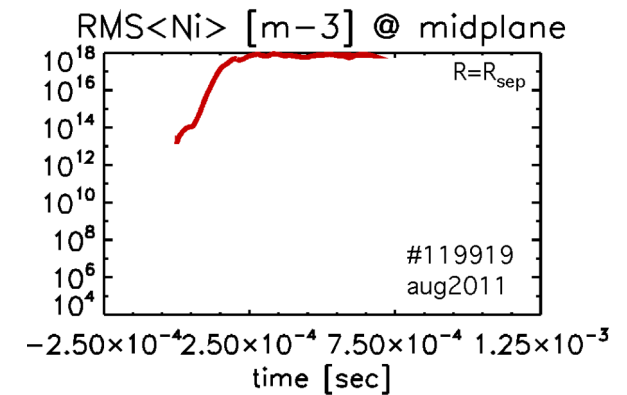
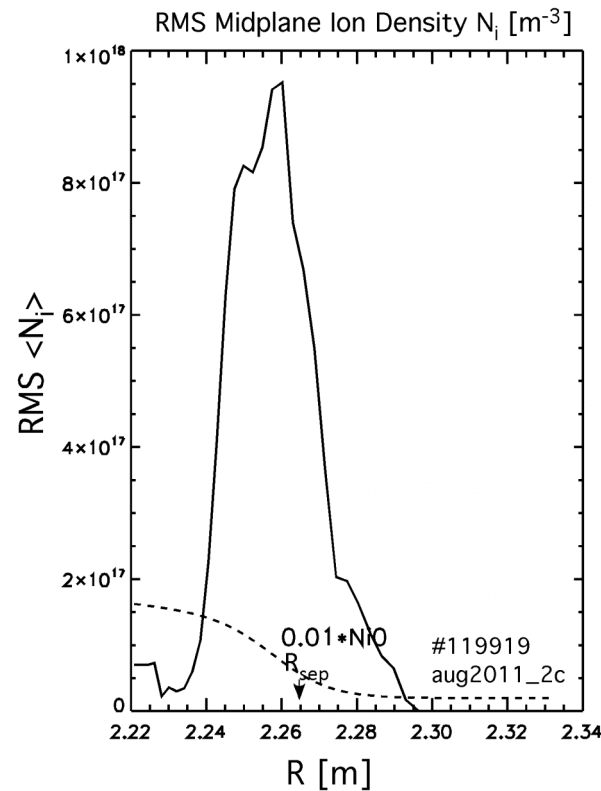
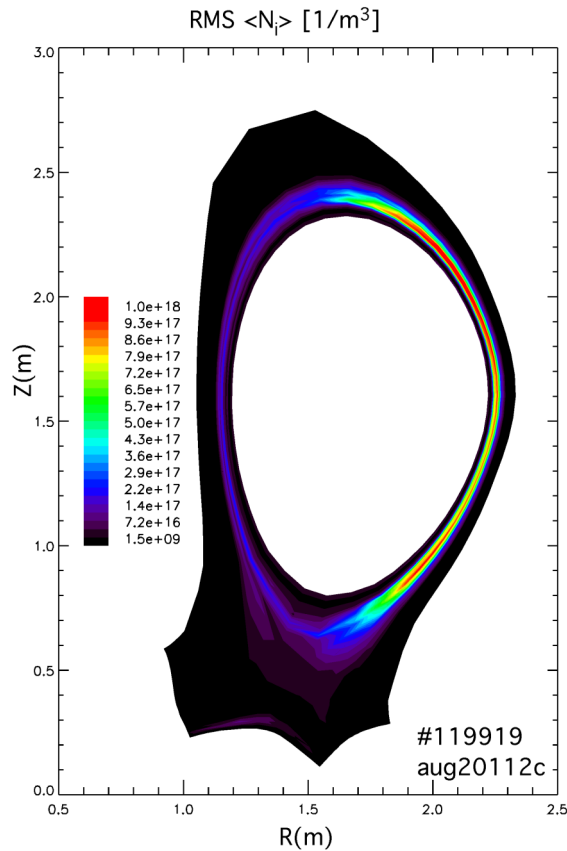
- Evolution of density fluctuations leading to saturated amplitudes and spectra



B. Cohen, et al., Int'l Sherwood 2012

Time-averaged ion density fluctuations in the midplane saturate at $\sim 10\%$ and peak near R_{sep}

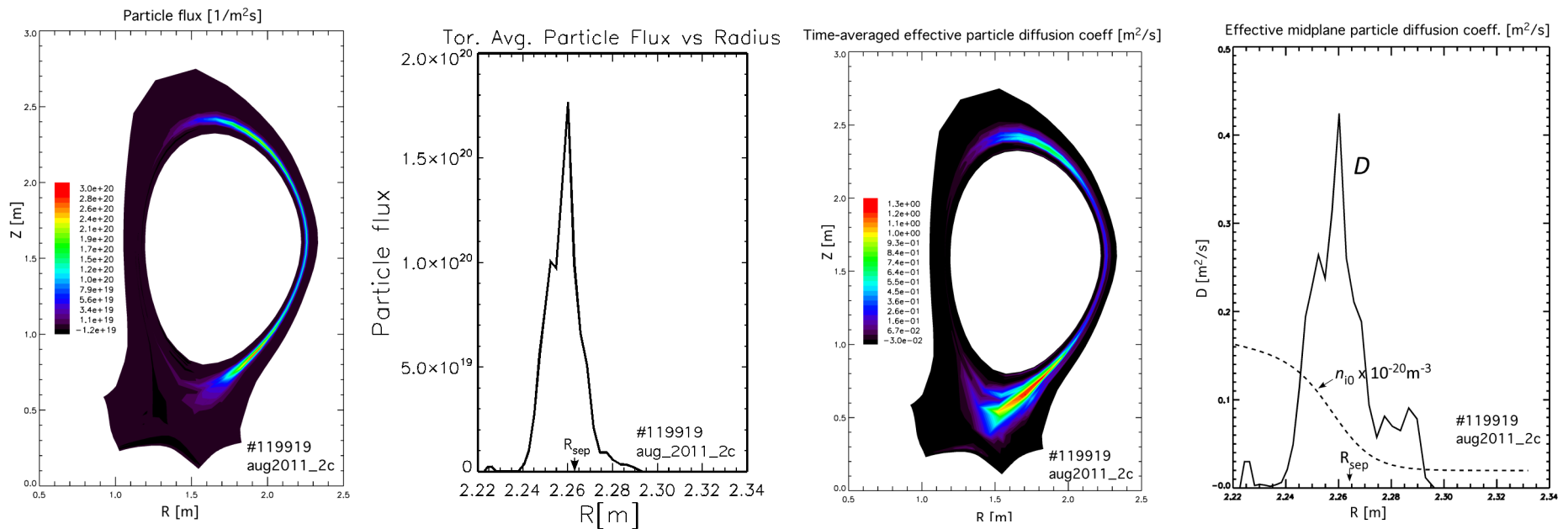
BOUT



- No T_e fluctuations

Time-averaged ion particle diffusion coefficient saturates at $O(0.4)$ m^2/s in the midplane and peaks near R_{sep}

BOUT



- No T_e fluctuations
- In this model with no temperature fluctuations and if $\nabla \ln(T_{eq}) = \nabla \ln(n_{eq})$, then $\chi_{conv} \approx (3/2)D$

Case #2: Include Advection of Temperature T_e in BOUT06 Equations for Drift Resistive Ballooning

- Consider the following simplified equation set in the BOUT06 framework:

$$\frac{\partial N_i}{\partial t} + (V_E + V_{\parallel}) \cdot \nabla N_i = \left(\frac{2c}{eB} \right) b_0 \times \kappa \cdot (\nabla P_e - N_i e \nabla \phi) + \nabla_{\parallel} (j_{\parallel} / e) - N_i \nabla_{\parallel} V_{\parallel i} \quad \text{RMS} \langle T_e \rangle \text{ [eV]}$$

$$\frac{\partial \varpi}{\partial t} + V_E \cdot \nabla \varpi = 2\omega_{ci} b_0 \times \kappa \cdot \nabla P + N_i Z_i e \frac{4\pi V_A^2}{c^2} \nabla_{\parallel} j_{\parallel}$$

$$\frac{\partial V_{\parallel e}}{\partial t} = -\frac{e}{m_e} E_{\parallel} - \frac{1}{Nm_e} (T_e \nabla_{\parallel} N_i) + 0.51 \nu_{ei} j_{\parallel}$$

$$\frac{\partial V_{\parallel i}}{\partial t} + V_E \cdot \nabla V_{\parallel i} = -\frac{1}{N_i M_i} \nabla_{\parallel} P$$

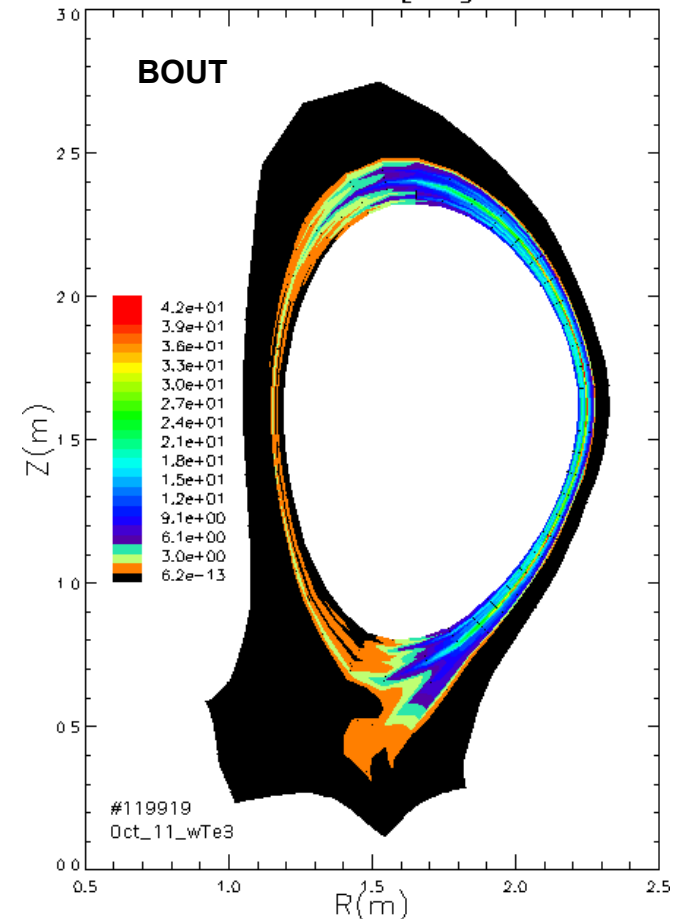
$$\frac{\partial T_e}{\partial t} + V_E \cdot \nabla T_e = 0$$

$$\mathbf{E} = -\frac{1}{c} \frac{\partial}{\partial t} \mathbf{A}_{\parallel} - \nabla \phi, \quad -\nabla_{\perp}^2 \mathbf{A}_{\parallel} = \frac{4\pi}{c} \mathbf{j}_{\parallel}, \quad \mathbf{B} = \nabla \times \mathbf{A}_{\parallel} + \mathbf{B}_0$$

$$\varpi = \nabla \cdot (e Z_i N_i \nabla \phi) \approx e Z_i N_i \nabla^2 \phi \quad \nabla_{\parallel} \approx \mathbf{b}_0 \cdot \nabla$$

- Electromagnetic with $\nabla_{\parallel} \approx \mathbf{b}_0 \cdot \nabla$
- Actual DIII-D geometry
- DIII-D - like fixed background profiles for shot 119919
- Includes T_e fluctuations

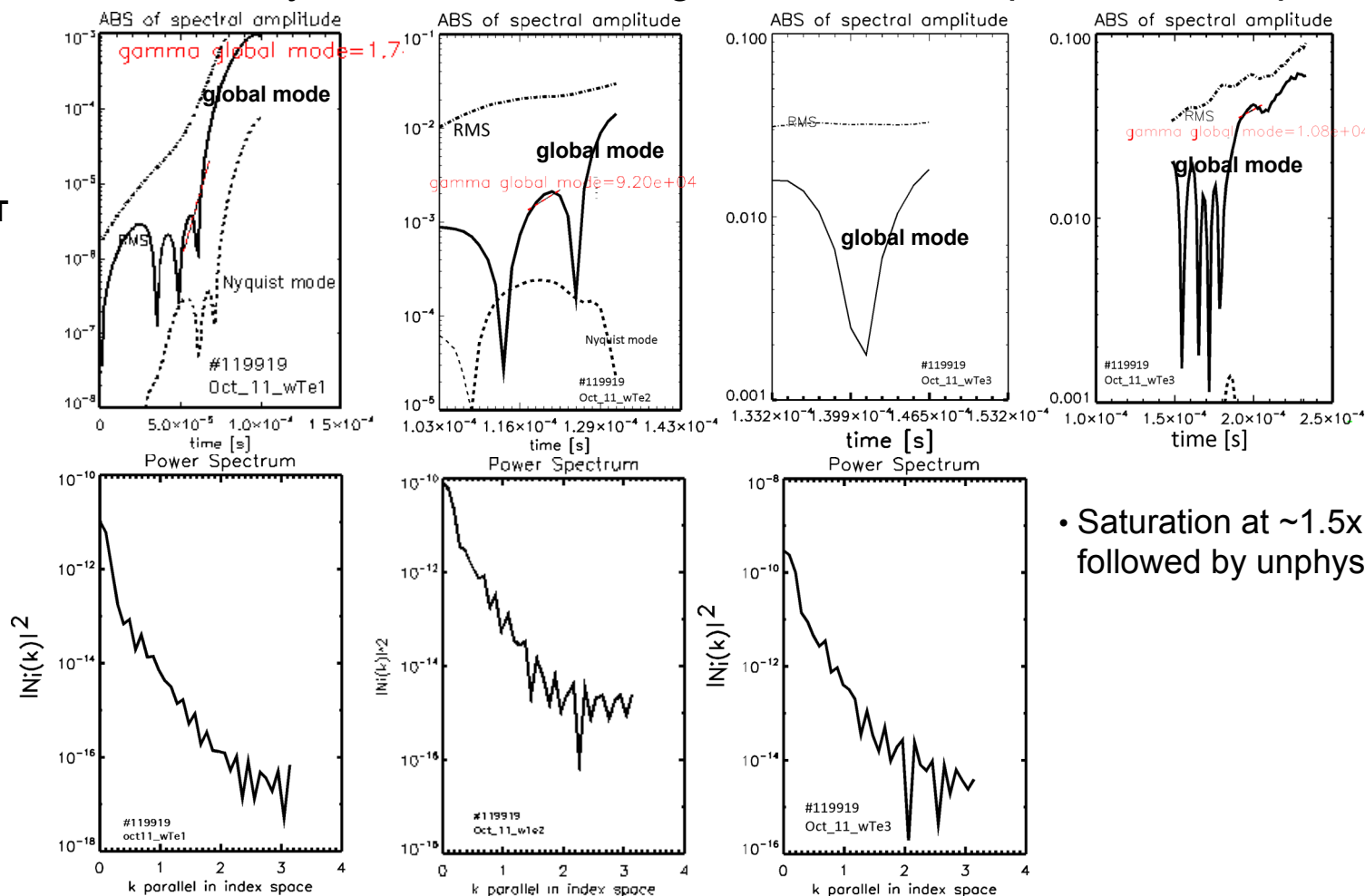
B. Cohen, et al., Int'l Sherwood 2012



BOUT-06 produces saturated turbulence for DIII-D geometry with T_e fluctuations

- Evolution of density fluctuations leading to saturated amplitudes and spectra

BOUT



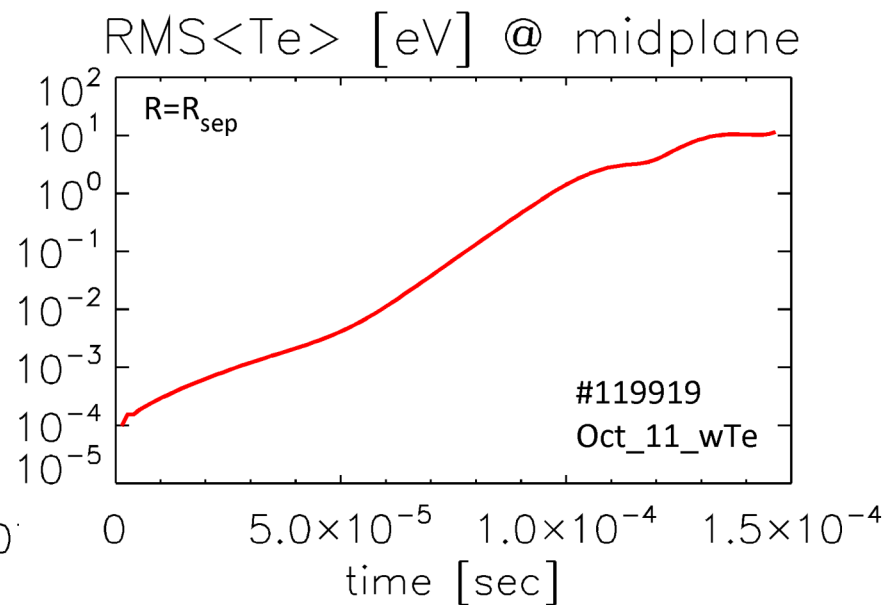
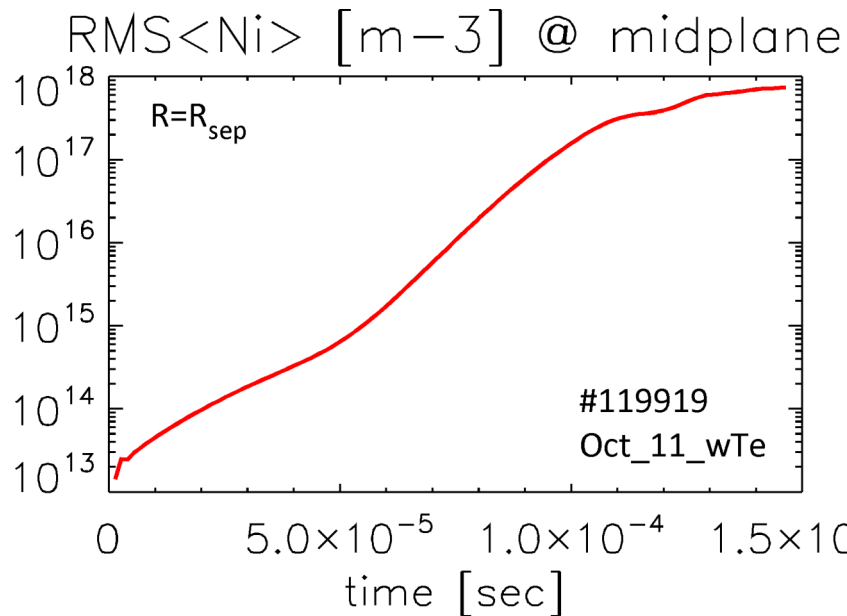
- Saturation at $\sim 1.5 \times 10^{-4}$ s followed by unphysical growth

- With T_e fluctuations

B. Cohen, et al., Int'l Sherwood 2012

Ion density and electron T_e fluctuations in the midplane saturate at $\sim 1.5 \times 10^{-4}$ sec

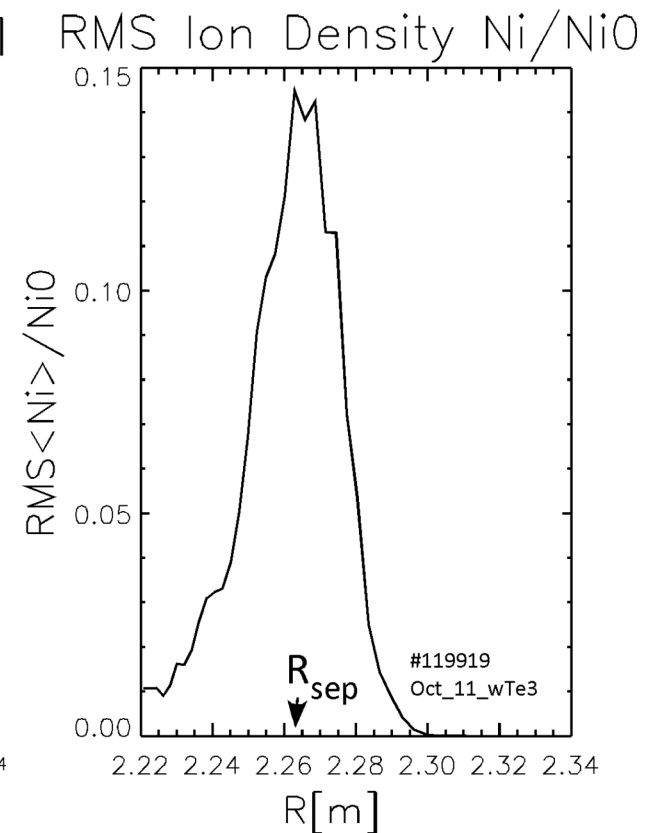
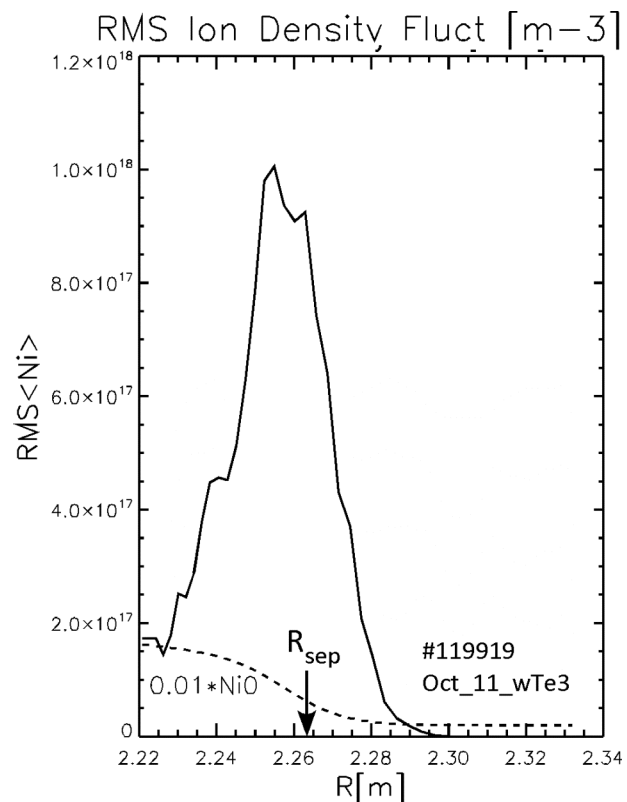
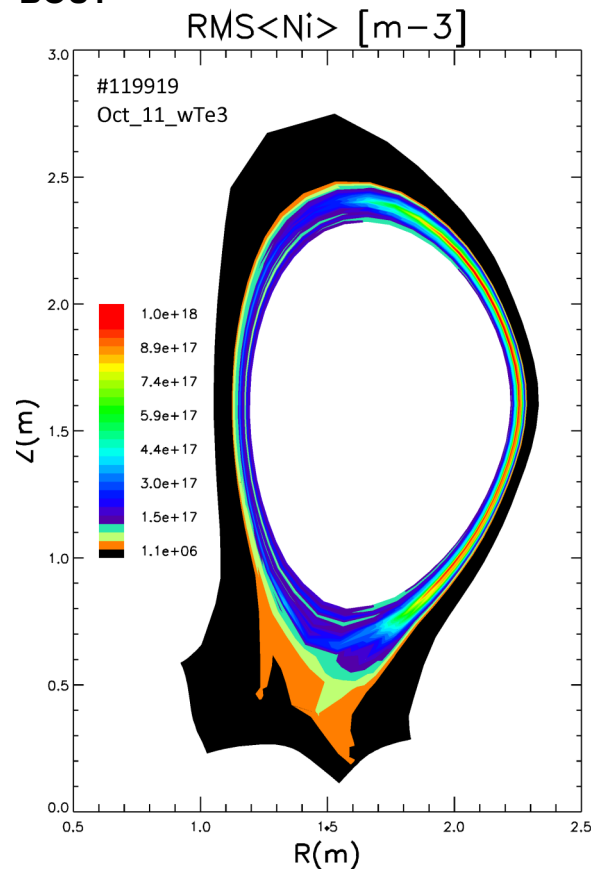
BOUT



- With T_e fluctuations

Time-averaged ion density fluctuations in the midplane saturate at $\sim 15\%$ relative amplitude and peak near R_{sep}

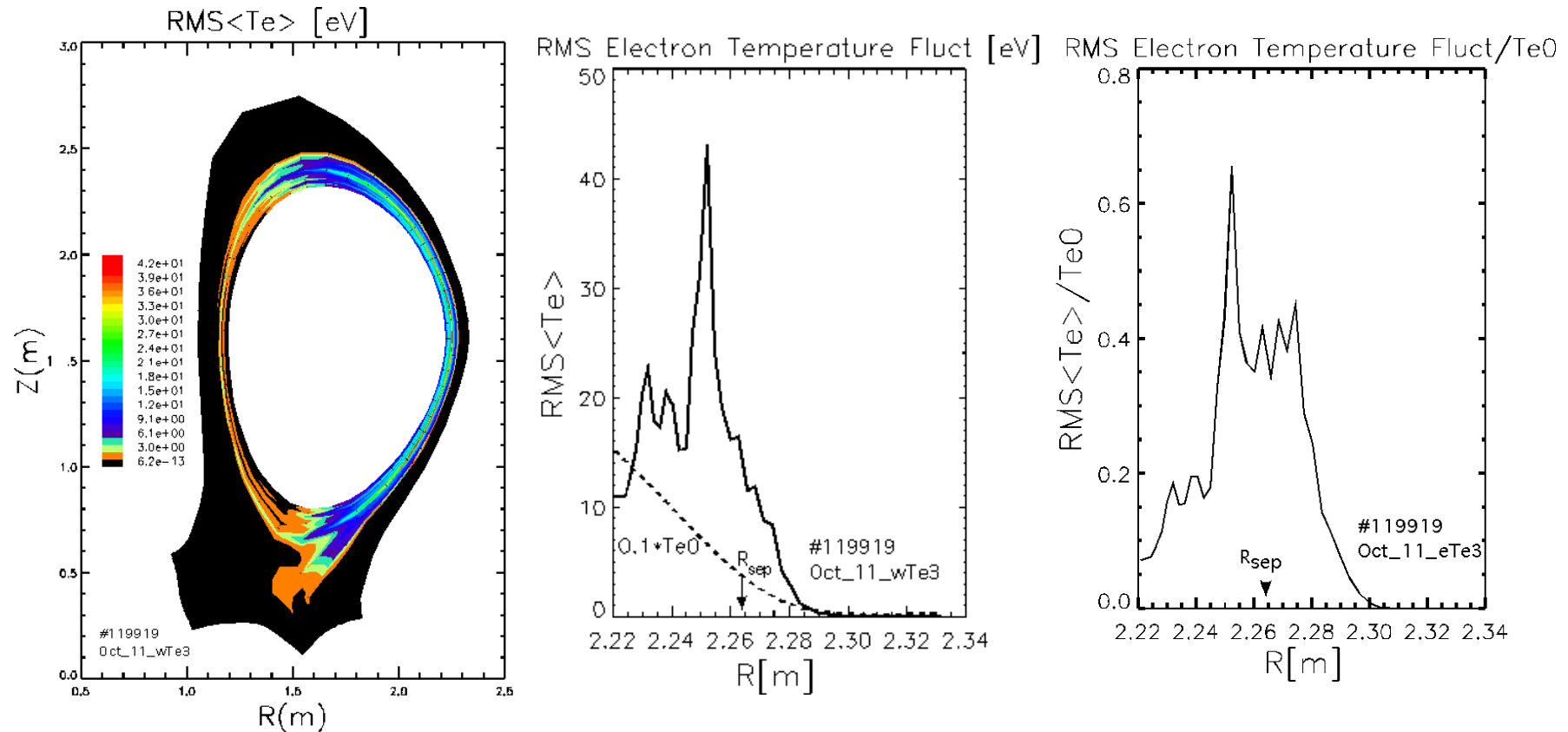
BOUT



- With T_e fluctuations

Time-averaged T_e fluctuations in the midplane saturate at ~40-60% relative amplitude and peak near R_{sep}

BOUT

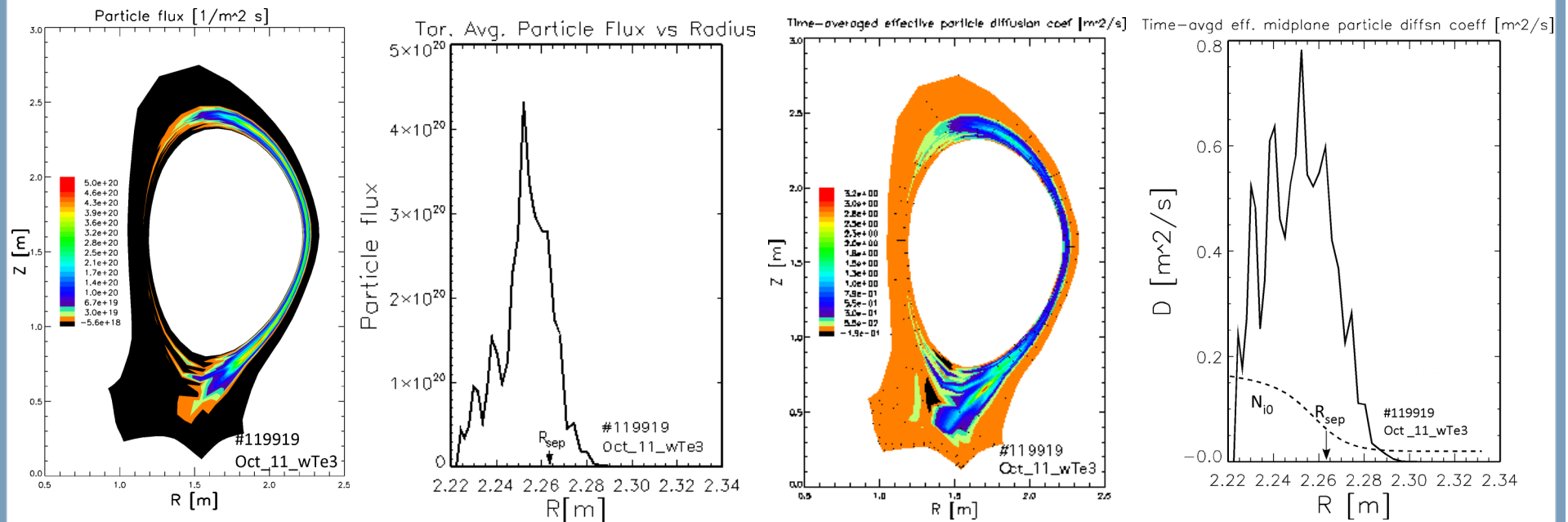


- With T_e fluctuations

B. Cohen, et al., Int'l Sherwood 2012

Time-averaged ion particle diffusion coefficient in the midplane saturates at $O(1) \text{ m}^2/\text{s}$ and peaks near R_{sep}

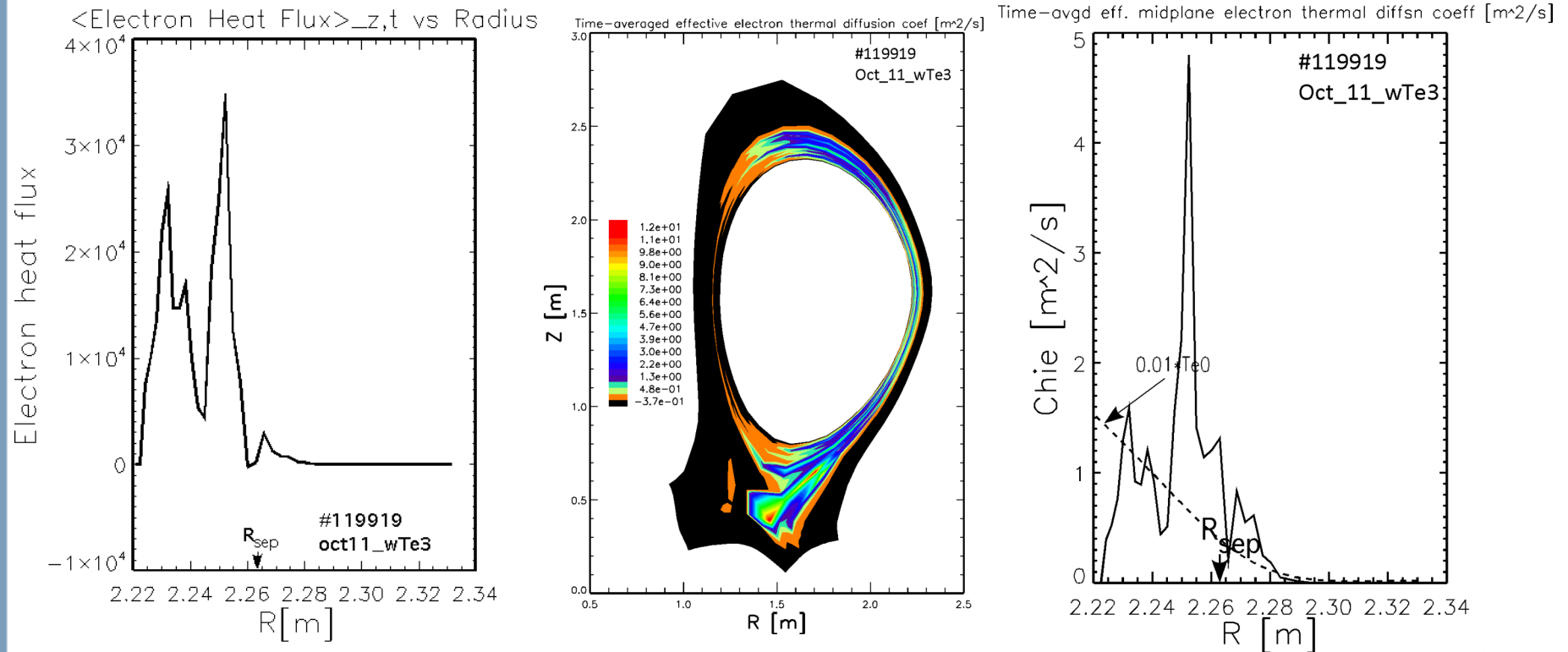
BOUT



- With T_e fluctuations

Time-averaged electron thermal diffusion coefficient in the midplane saturates at 1-5 m²/s and peaks near R_{sep}

- Bout with T_e fluctuations



Note : Here heat flux (conductive) = $N_0 \langle \delta \tilde{v}_r \delta T_e \rangle_{tor,t}$, and $\chi_e = -N_0 \langle \delta \tilde{v}_r \delta T_e \rangle_{tor,t} / N_0 \nabla T_{e0}$

Case #3: Include Advection of T_e in BOUT06 Equations for Drift Resistive Ballooning with Parallel Electron Thermal Conduction

- Consider the following simplified equation set in the BOUT06 framework:

$$\frac{\partial N_i}{\partial t} + (V_E + V_{\parallel}) \cdot \nabla N_i = \left(\frac{2c}{eB} \right) b_0 \times \kappa \cdot (\nabla P_e - N_i e \nabla \varphi) + \nabla_{\parallel} (j_{\parallel} / e) - N_i \nabla_{\parallel} V_{\parallel i}$$

$$\frac{\partial \varpi}{\partial t} + V_E \cdot \nabla \varpi = 2\omega_{ci} b_0 \times \kappa \cdot \nabla P + N_i Z_i e \frac{4\pi V_A^2}{c^2} \nabla_{\parallel} j_{\parallel}$$

$$\frac{\partial V_{\parallel e}}{\partial t} = -\frac{e}{m_e} E_{\parallel} - \frac{1}{Nm_e} (T_e \nabla_{\parallel} N_i) + 0.51 \nu_{ei} j_{\parallel}$$

$$\frac{\partial V_{\parallel i}}{\partial t} + V_E \cdot \nabla V_{\parallel i} = -\frac{1}{N_i M_i} \nabla_{\parallel} P$$

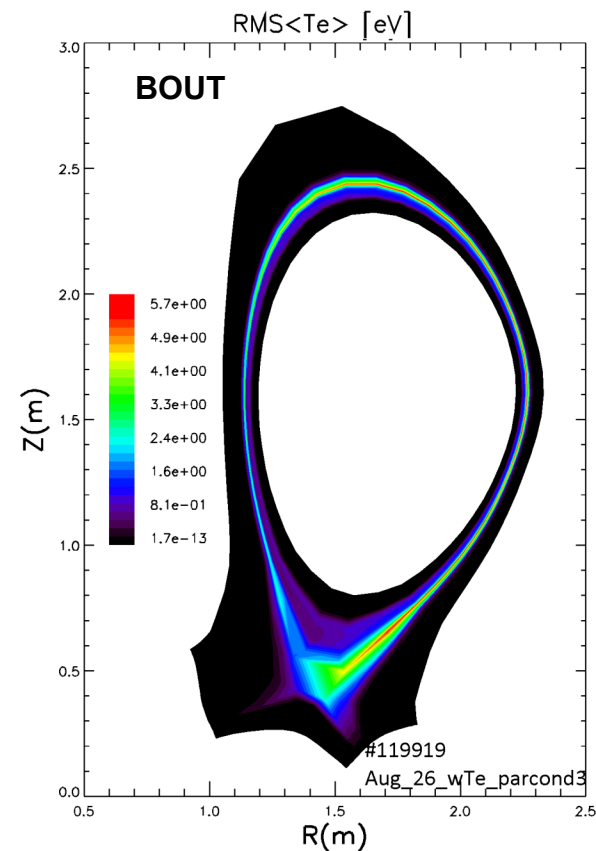
$$\frac{\partial T_e}{\partial t} + V_E \cdot \nabla T_e = \frac{2}{3N_0} \nabla \cdot (\kappa_{\parallel}^e \nabla T_e), \quad \kappa_{\parallel}^e = 3.2 \frac{N_0 T_{e0} \tau_e}{m_e}$$

$$\mathbf{E} = -\frac{1}{c} \frac{\partial}{\partial t} \mathbf{A}_{\parallel} - \nabla \varphi, \quad -\nabla_{\perp}^2 \mathbf{A}_{\parallel} = \frac{4\pi}{c} \mathbf{j}_{\parallel}, \quad \mathbf{B} = \nabla \times \mathbf{A}_{\parallel} + \mathbf{B}_0$$

$$\varpi = \nabla \cdot (e Z_i N_i \nabla \varphi) \approx e Z_i N_i \nabla^2 \varphi \quad \nabla_{\parallel} = \mathbf{b}_0 \cdot \nabla$$

- Electromagnetic with $\nabla_{\parallel} = \mathbf{b}_0 \cdot \nabla$
- Actual DIII-D geometry
- DIII-D - like fixed background profiles for shot #119919
- Includes T_e fluctuations & parallel heat conduction

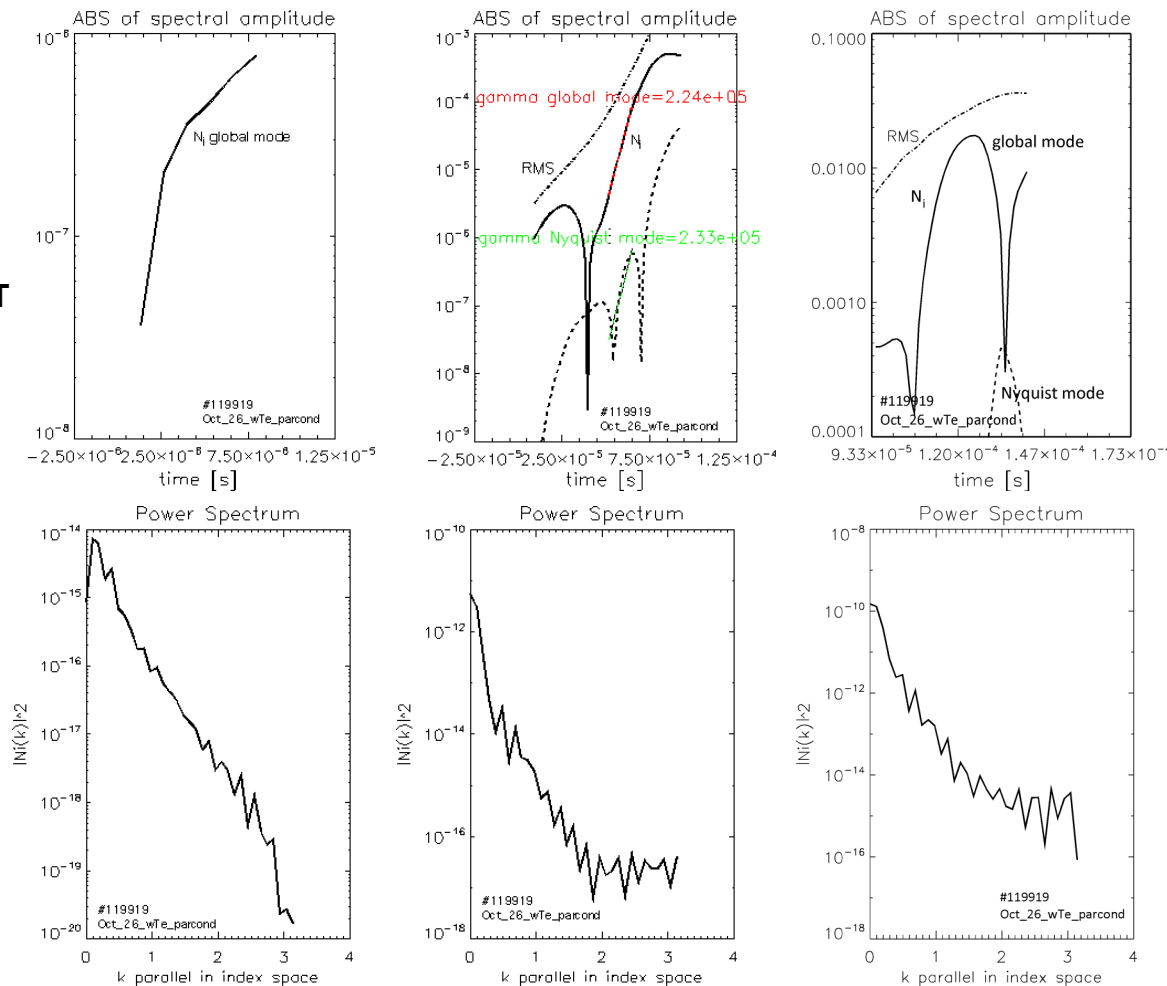
B. Cohen, et al., Int'l Sherwood 2012



BOUT-06 produces saturated turbulence for DIII-D geometry with T_e fluctuations and electron parallel thermal conduction

- Evolution of density fluctuations leading to saturated amplitudes and spectra

BOUT



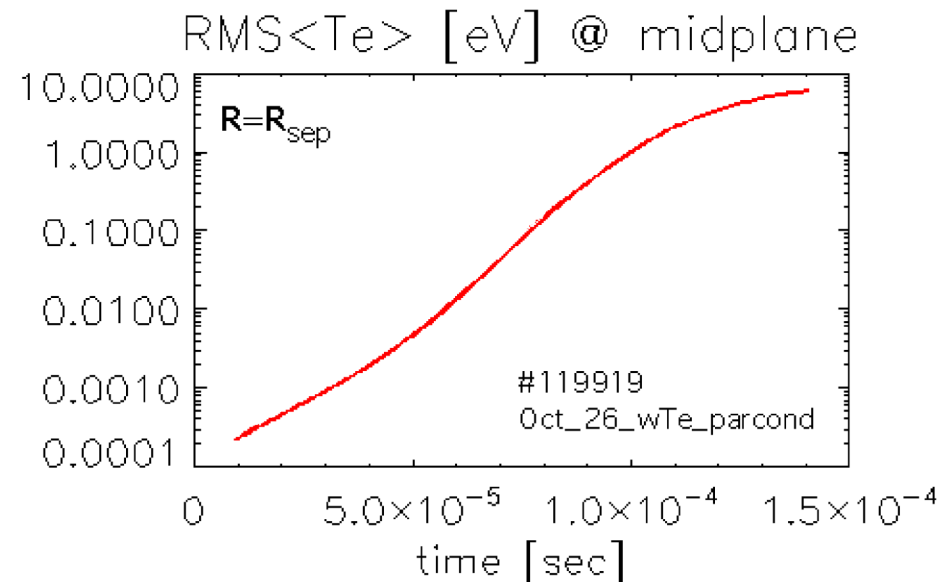
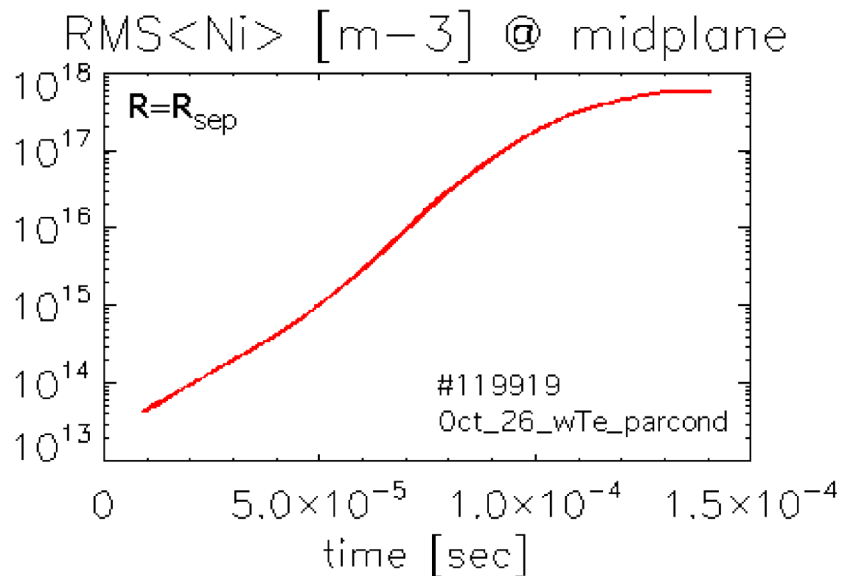
- Saturation at $\sim 1.5 \times 10^{-4}$ s

- With T_e fluctuations and electron parallel thermal conduction

B. Cohen, et al., Int'l Sherwood 2012

History of rms fluctuation amplitudes in midplane at separatrix with electron parallel thermal conduction

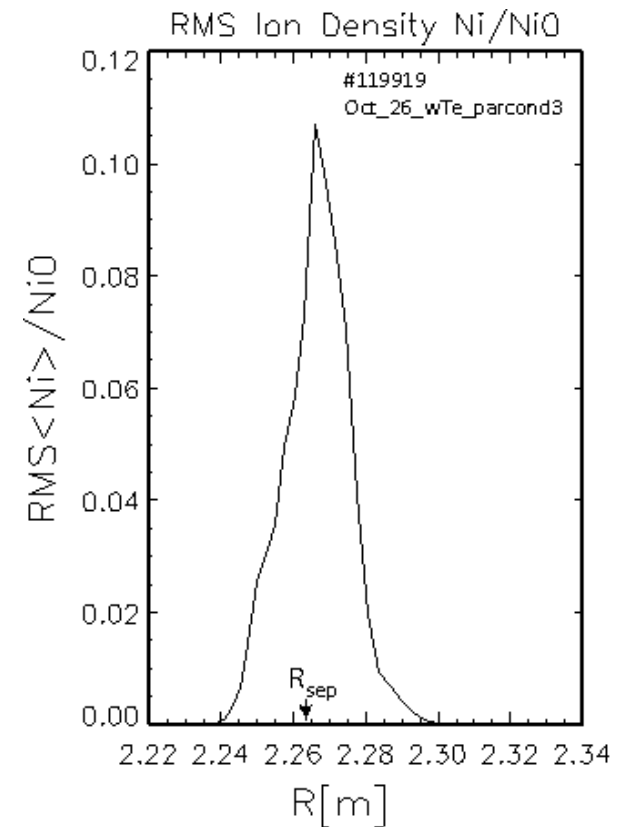
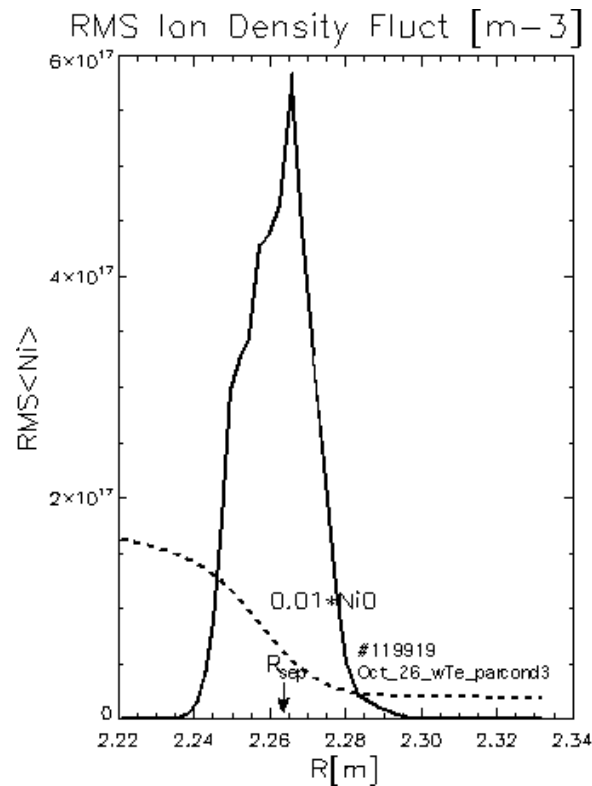
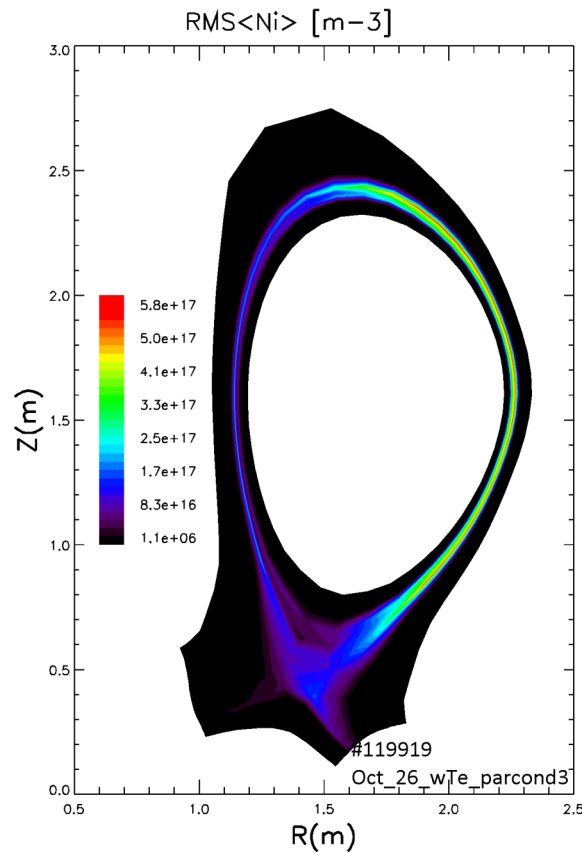
BOUT



- With T_e fluctuations and electron parallel thermal conduction

Time-averaged ion density fluctuations in the midplane saturate at $\sim 11\%$ and peak near R_{sep}

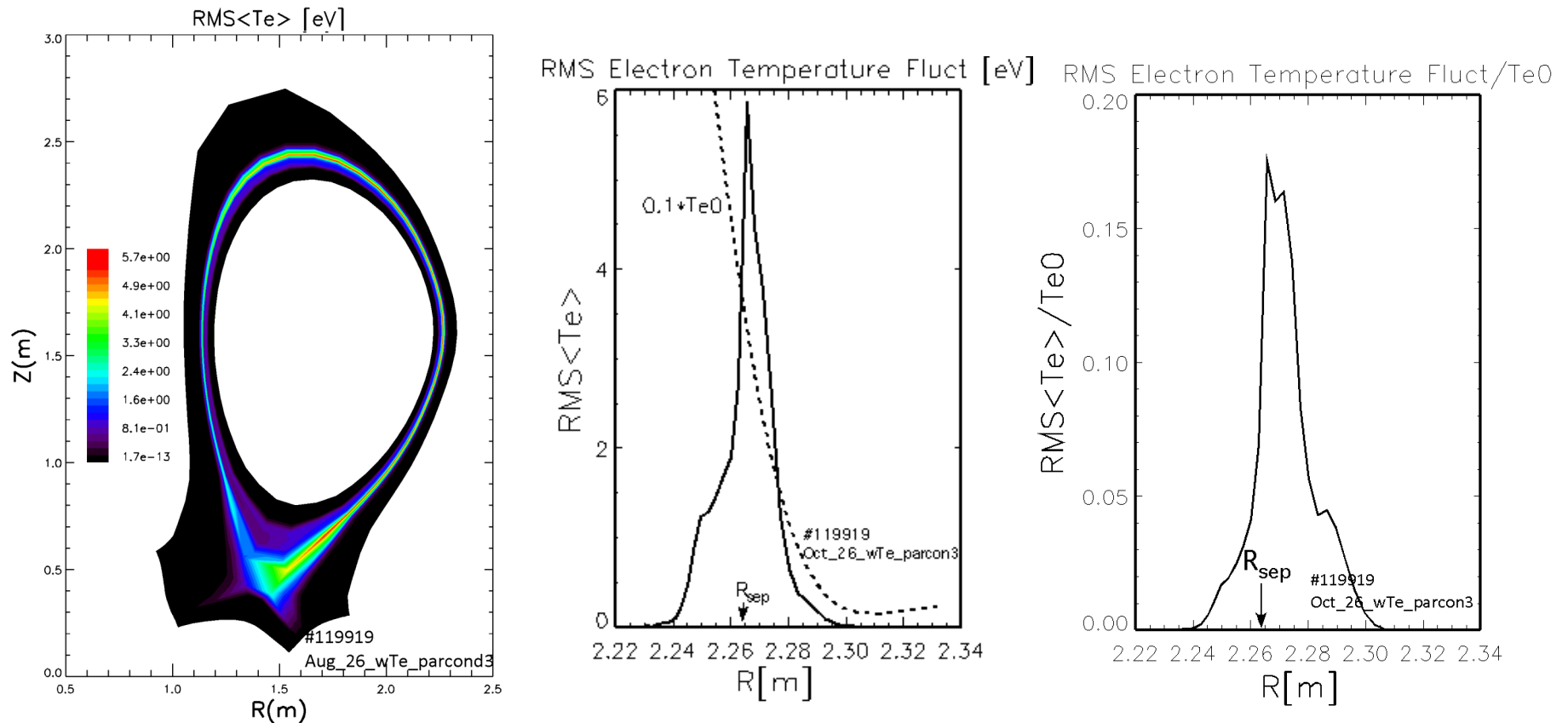
BOUT



- With T_e fluctuations and electron parallel thermal conduction

Time-averaged T_e fluctuations in the midplane peak near the R_{sep} and saturate at $\sim 18\%$ relative amplitude

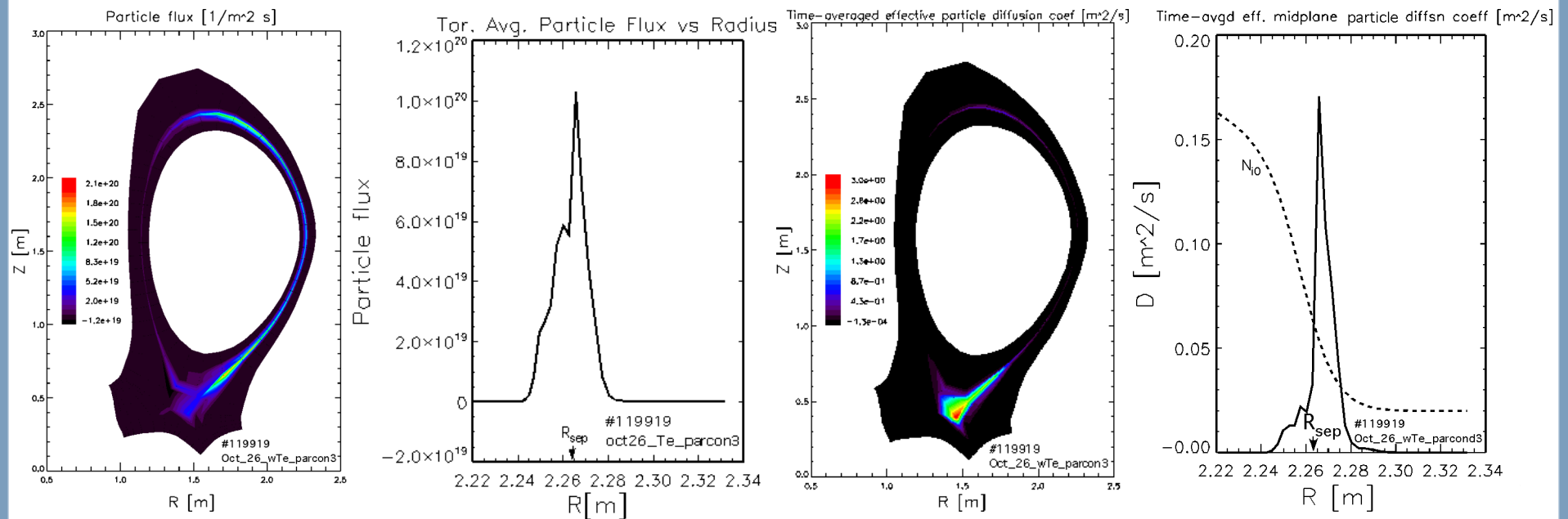
BOUT



- With T_e fluctuations and electron parallel thermal conduction

Time-averaged ion particle diffusion coefficient in the midplane saturates at $< 0.2 \text{ m}^2/\text{s}$ and peaks near R_{sep}

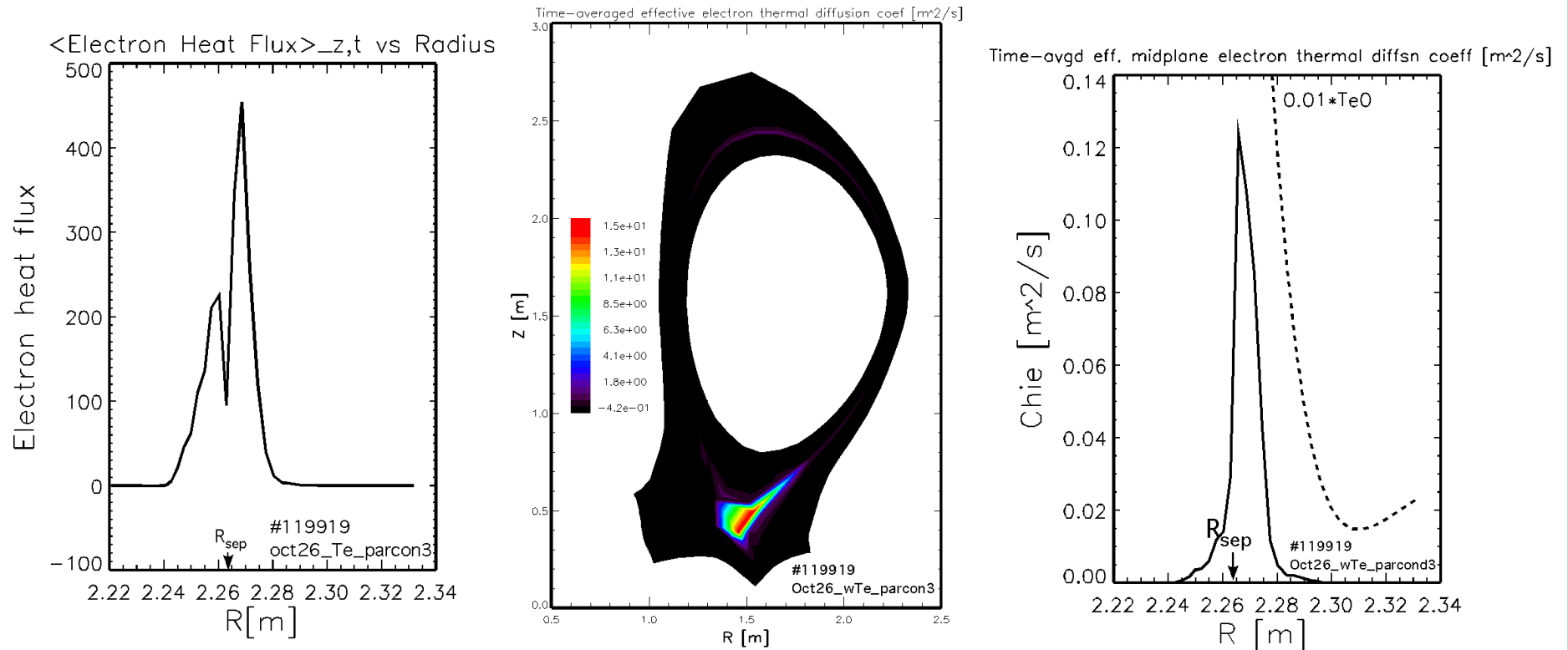
BOUT



- With T_e fluctuations and electron parallel thermal conduction

Time-averaged electron thermal diffusion coefficient in the midplane saturates at $\sim 0.1 \text{ m}^2/\text{s}$ and peaks near R_{sep}

BOUT



Note : Here heat flux (conductive) = $N_0 < \delta \tilde{v}_r \delta T_e >_{\text{tor},t}$, and $\chi_e = -N_0 < \delta \tilde{v}_r \delta T_e >_{\text{tor},t} / N_0 \nabla T_{e0}$

- With T_e fluctuations and electron parallel thermal conduction

Case #4: Include Advection of Temperature T_e in BOUT06 Equations for Drift Resistive Ballooning with Magnetic Flutter

- Consider the following simplified equation set in the BOUT06 framework:

$$\frac{\partial N_i}{\partial t} + (V_E + V_{\parallel}) \cdot \nabla N_i = \left(\frac{2c}{eB} \right) b_0 \times \kappa \cdot (\nabla P_e - N_i e \nabla \varphi) + \nabla_{\parallel} (j_{\parallel} / e) - N_i \nabla_{\parallel} V_{\parallel i}$$

$$\frac{\partial \varpi}{\partial t} + V_E \cdot \nabla \varpi = 2\omega_{ci} b_0 \times \kappa \cdot \nabla P + N_i Z_i e \frac{4\pi V_A^2}{c^2} \nabla_{\parallel} j_{\parallel}$$

$$\frac{\partial V_{\parallel e}}{\partial t} = -\frac{e}{m_e} E_{\parallel} - \frac{1}{Nm_e} (T_e \nabla_{\parallel} N_i) + 0.51 \nu_{ei} j_{\parallel}$$

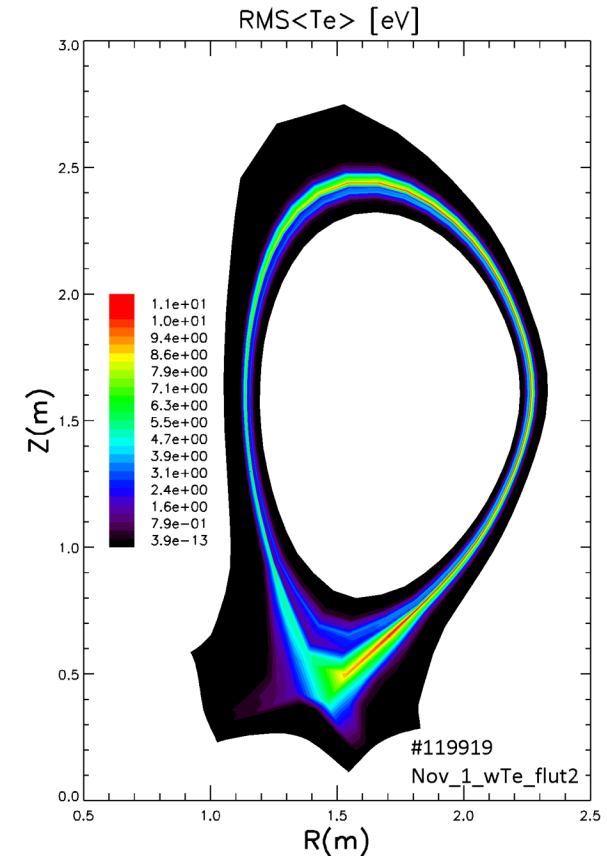
$$\frac{\partial V_{\parallel i}}{\partial t} + V_E \cdot \nabla V_{\parallel i} = -\frac{1}{N_i M_i} \nabla_{\parallel} P$$

$$\frac{\partial T_e}{\partial t} + V_E \cdot \nabla T_e = \frac{2}{3N_0} \nabla \cdot (\kappa_{\parallel}^e \nabla_{\parallel} T_e), \quad \kappa_{\parallel}^e = 3.2 \frac{n T_{e0} \tau_e}{m_e}$$

$$\mathbf{E} = -\frac{1}{c} \frac{\partial}{\partial t} \mathbf{A}_{\parallel} - \nabla \varphi, \quad -\nabla_{\perp}^2 \mathbf{A}_{\parallel} = \frac{4\pi}{c} \mathbf{j}_{\parallel}, \quad \mathbf{B} = \nabla \times \mathbf{A}_{\parallel} + \mathbf{B}_0$$

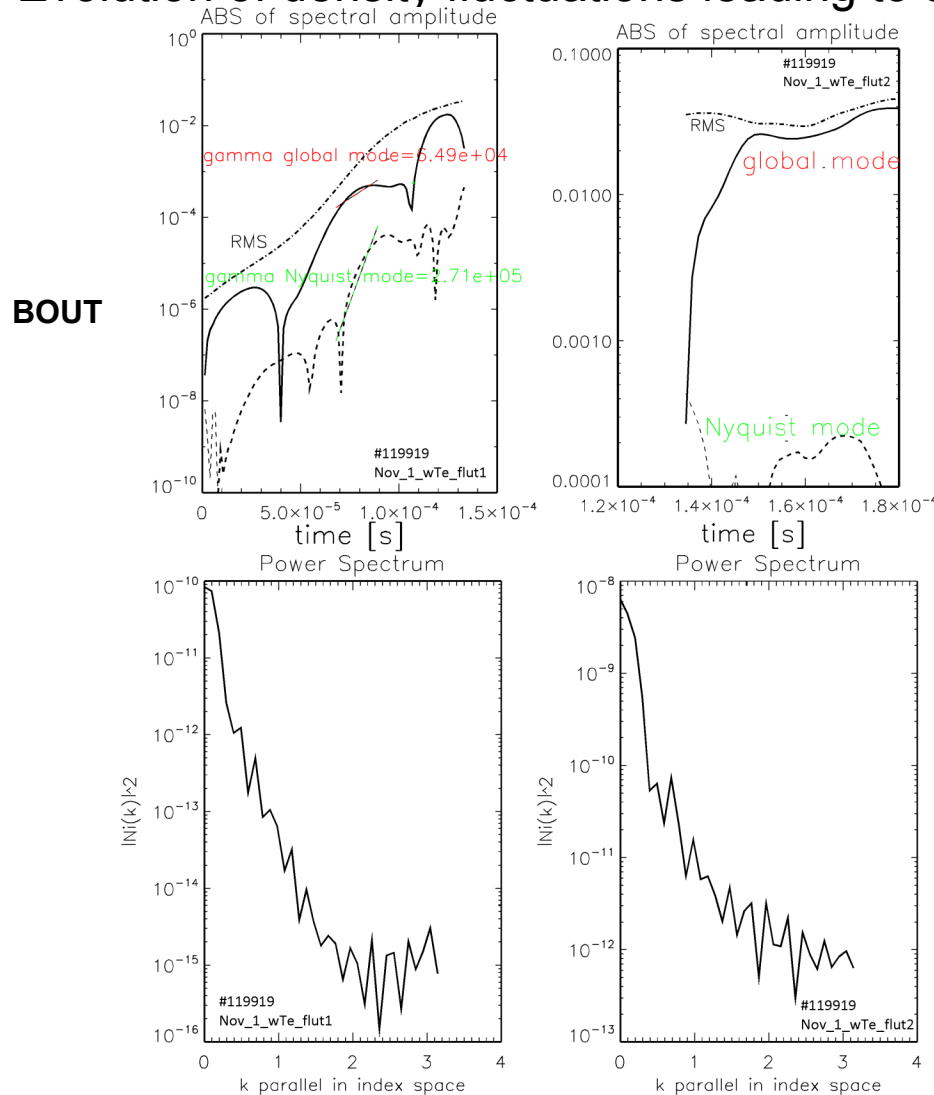
$$\varpi = \nabla \cdot (e Z_i N_i \nabla \varphi) \approx e Z_i N_i \nabla^2 \varphi \quad \nabla_{\parallel} = \mathbf{b}_0 \cdot \nabla + \tilde{\mathbf{b}} \cdot \nabla$$

- Electromagnetic with $\nabla_{\parallel} = \mathbf{b}_0 \cdot \nabla + \tilde{\mathbf{b}} \cdot \nabla$ in the vorticity eqn.
- Actual DIII-D geometry
- DIII-D - like fixed background profiles for shot 119919
- Includes T_e fluctuations and parallel heat conduction



BOUT-06 produces saturated turbulence for DIII-D geometry with δT_e , parallel thermal conduction, and magnetic flutter

- Evolution of density fluctuations leading to saturated amplitudes and spectra

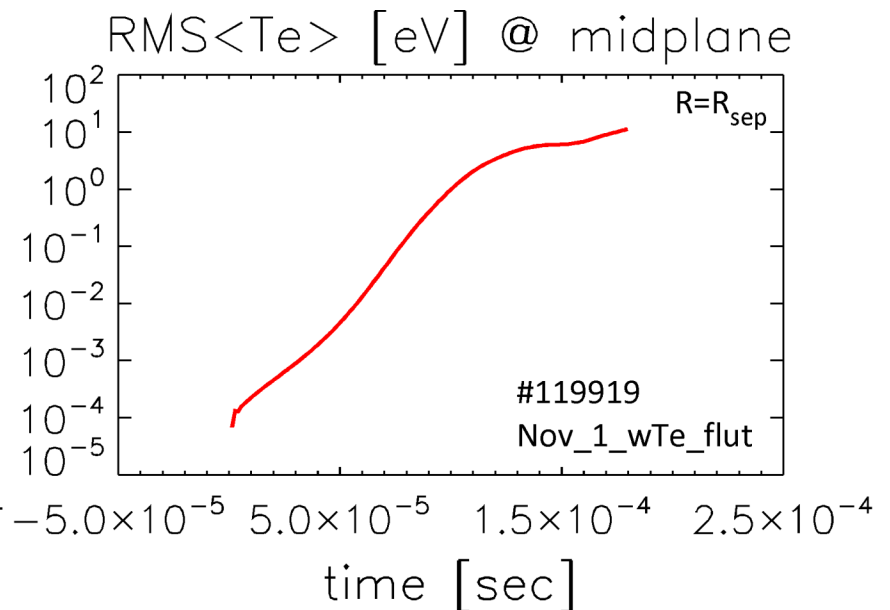
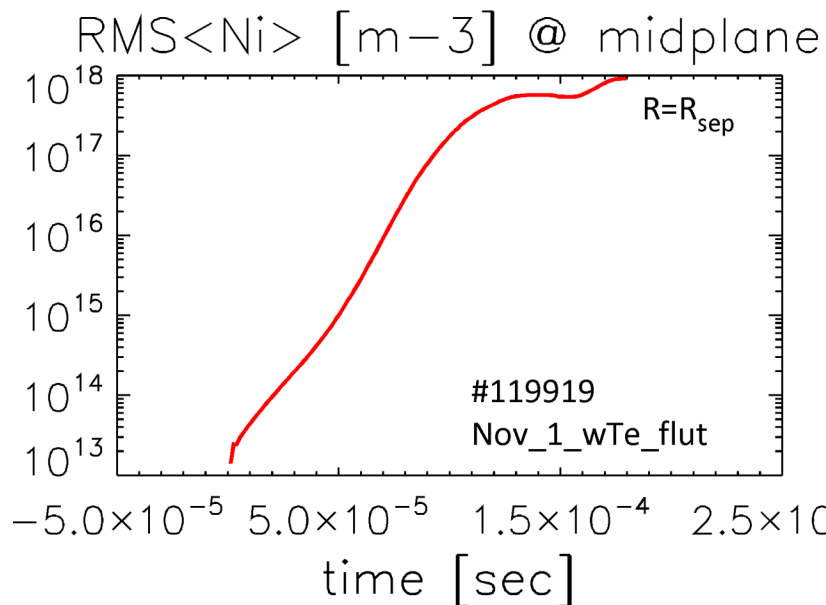


- Saturation at $\sim 1.5 \times 10^{-4}$ s

- With T_e fluctuations, electron parallel thermal conduction, and $\nabla_{\parallel} = \mathbf{b}_0 \cdot \nabla + \tilde{\mathbf{b}} \cdot \nabla$

History of rms fluctuation amplitudes in midplane at separatrix with electron parallel thermal conduction and magnetic flutter

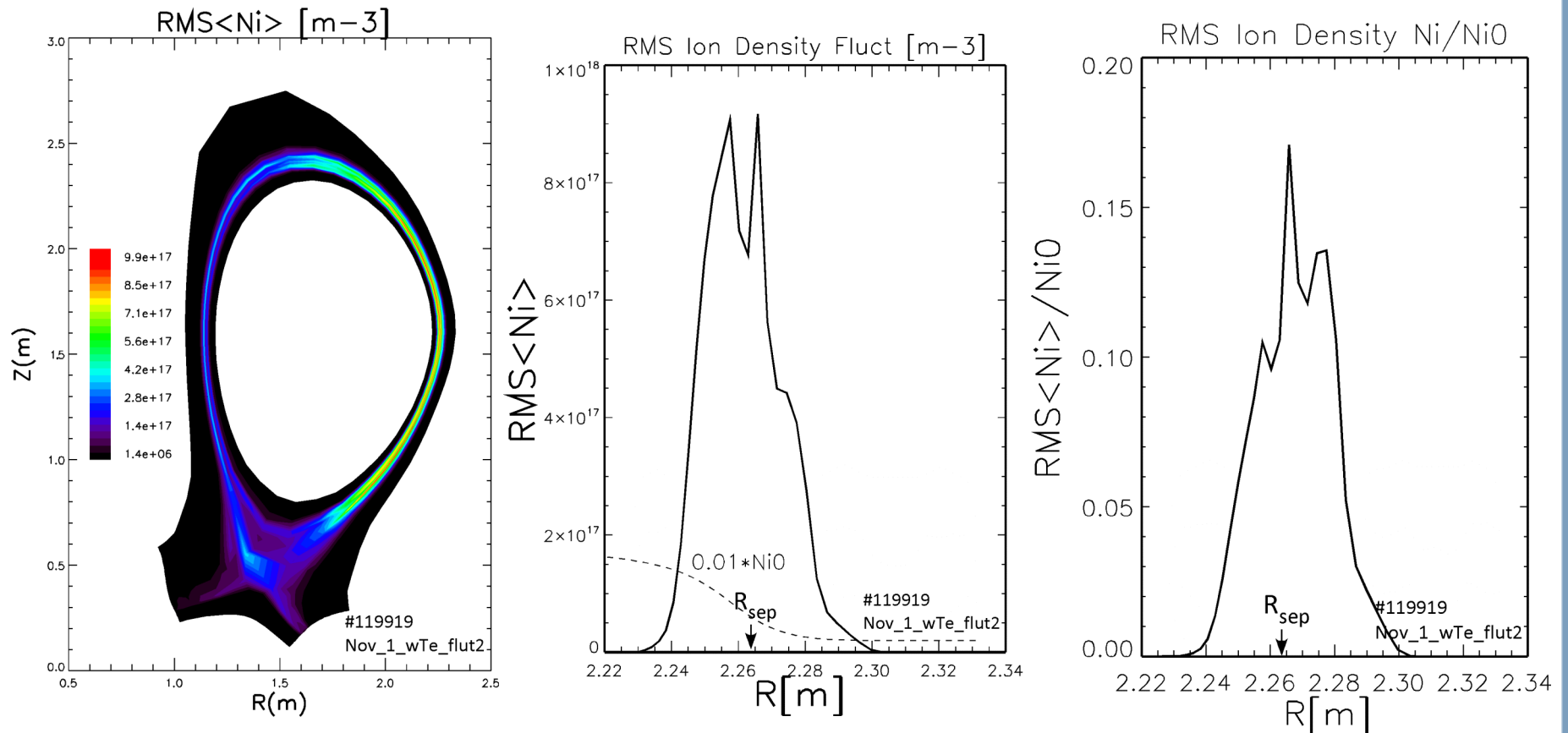
BOUT



- With T_e fluctuations, electron parallel thermal conduction, and $\nabla_{\parallel} = \mathbf{b}_0 \cdot \nabla + \tilde{\mathbf{b}} \cdot \nabla$ in vorticity equation

Time-averaged ion density fluctuations in the midplane saturate at ~10-15% and peak near R_{sep}

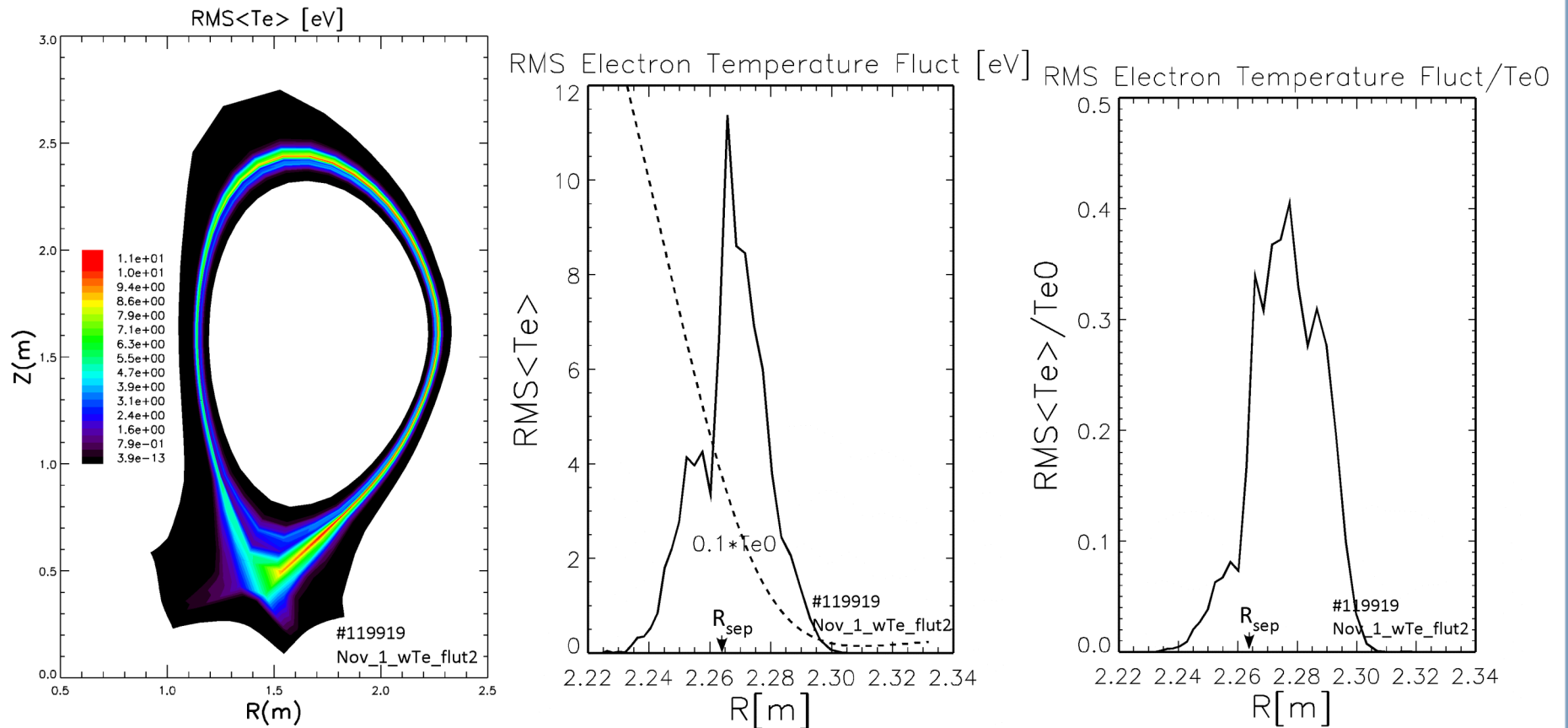
BOUT



- With T_e fluctuations, electron parallel thermal conduction, and $\nabla_{\parallel} = \mathbf{b}_0 \cdot \nabla + \tilde{\mathbf{b}} \cdot \nabla$

Time-averaged T_e fluctuations in the midplane peak near the R_{sep} and saturate at ~25-40% relative amplitude

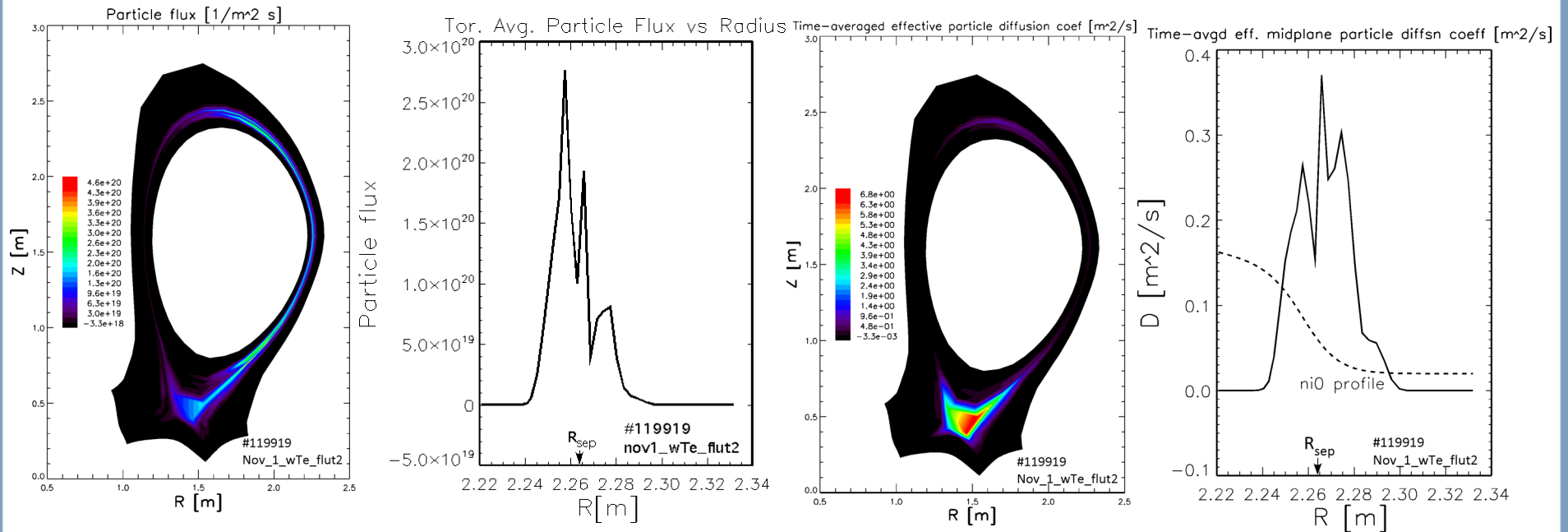
BOUT



- With T_e fluctuations, electron parallel thermal conduction, and $\nabla_{||} = \mathbf{b}_0 \cdot \nabla + \tilde{\mathbf{b}} \cdot \nabla$

Time-averaged ion particle diffusion coefficient in the midplane saturates at $< 0.3\text{-}0.4 \text{ m}^2/\text{s}$

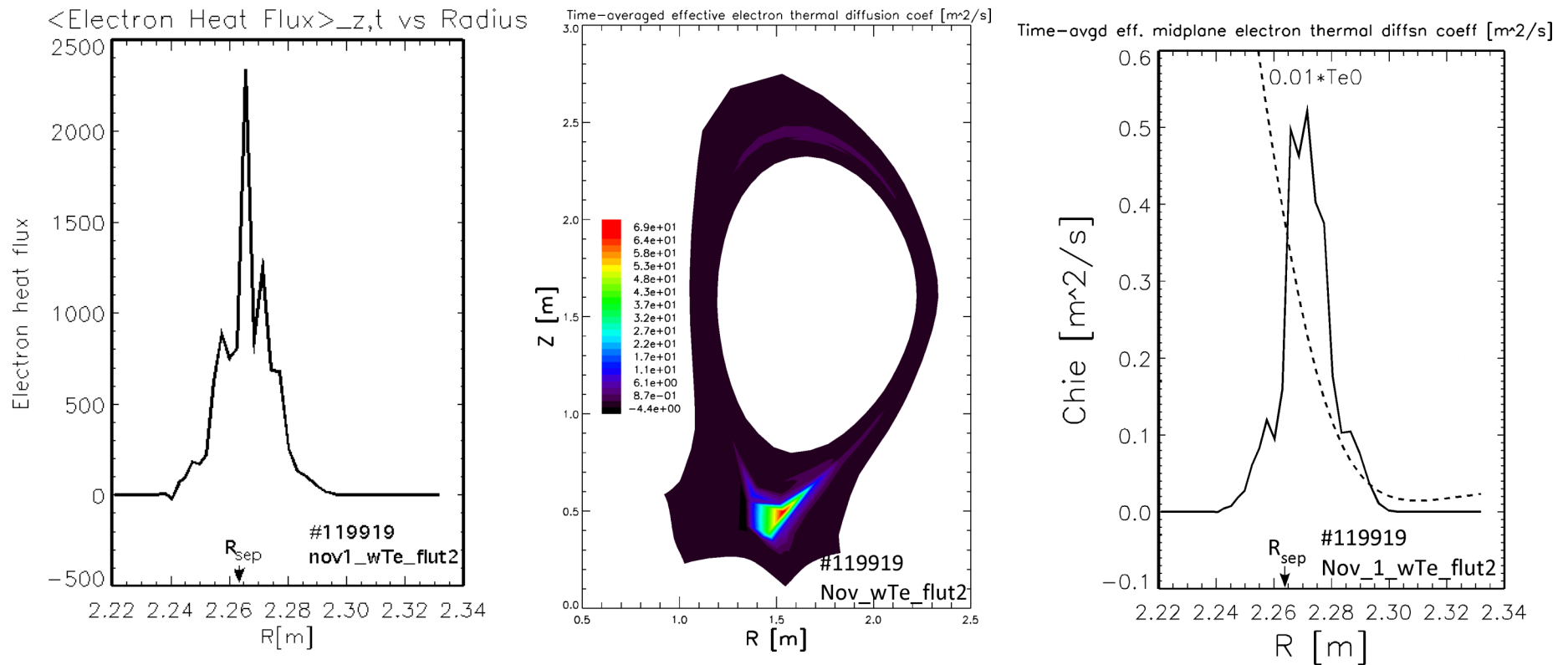
BOUT



- With T_e fluctuations, electron parallel thermal conduction, and $\nabla_{\parallel} = \mathbf{b}_0 \cdot \nabla + \tilde{\mathbf{b}} \cdot \nabla$

Time-averaged electron thermal diffusion coefficient in the midplane saturates at $\sim 0.5 \text{ m}^2/\text{s}$

BOUT

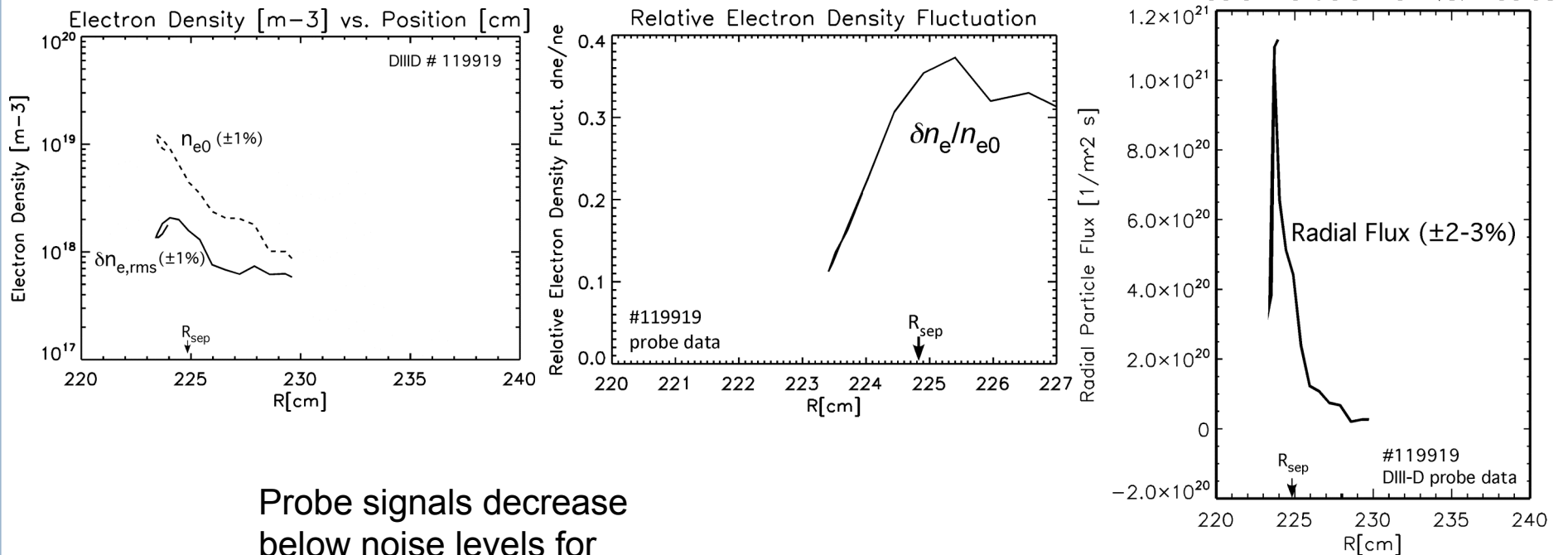


Note : Here heat flux (conductive) = $N_0 \langle \delta \tilde{v}_r \delta T_e \rangle_{\text{tor},t}$, and $\chi_e = -N_0 \langle \delta \tilde{v}_r \delta T_e \rangle_{\text{tor},t} / N_0 \nabla T_{e0}$

- With T_e fluctuations, electron parallel thermal conduction, and $\nabla_{\parallel} = \mathbf{b}_0 \cdot \nabla + \tilde{\mathbf{b}} \cdot \nabla$

Langmuir Probe Data for DIII-D #119919 (J. Boedo)

Electron density and radial particle flux vs. radius -- relative density fluctuations exceed ~20%

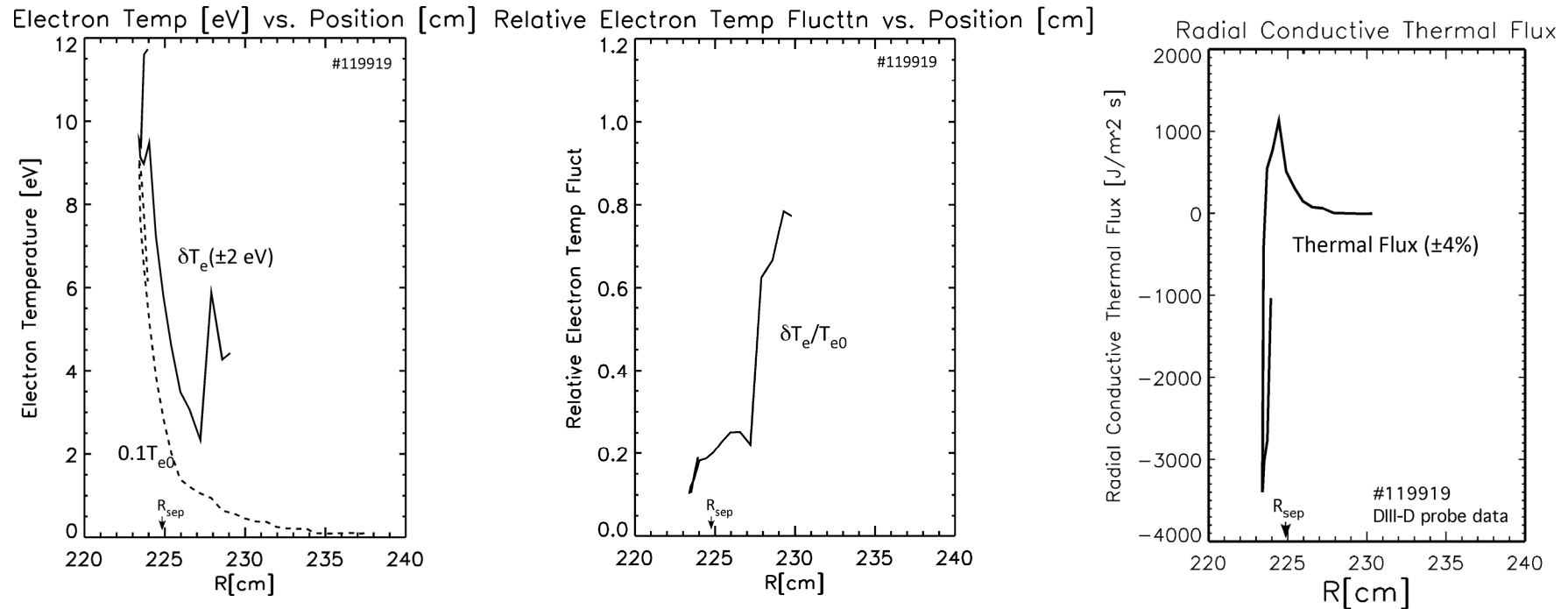


Probe signals decrease
below noise levels for
 $R > 229$ cm.

Typical experimental rms density fluctuations at the separatrix are 24-50%
There is evidence that δn and the radial flux in the midplane peak near R_{sep} as in BOUT results.

Langmuir Probe Data for DIII-D #119919 (J. Boedo)

Electron temperature fluctuations in midplane exceed 10%



Probe signals decrease below noise levels for $R > 229 \text{ cm}$.

Typical experimental rms δT_e fluctuations at the separatrix are 10-25% δT_e and the probe fluxes in the midplane usually peak near the separatrix as in BOUT results.

Summary: As the physics model becomes more complete, the agreement of BOUT results with DIII-D probe data improves

- BOUT algorithmic issues -- control of an odd-even numerical contamination allows us to perform DIII-D simulations
- Comparison of suite of BOUT simulations to shot #119919: peak values in midplane at saturation near R_{sep}

Bout simulation	$\langle \delta N_i \rangle_{rms}$ (10^{18} m^{-3})	$\langle \delta T_e \rangle_{rms}$ (eV)	Radial Particle Flux ($10^{20} / \text{m}^2 \text{ s}$)	D_r (m^2/s) local	Radial Heat Flux $= \frac{3}{2} N_0 \langle \delta \tilde{v}_r \delta \tilde{T}_e \rangle$ ($10^3 \text{ J/m}^2 \text{ s}$)	χ_e (m^2/s), local (conductive)
#1: $\delta T_e = 0$	0.95	N/A	1.8	0.4	N/A	N/A
#2: $\delta T_e \neq 0$ $\kappa_{ e} = 0$	1.0	43	4.3	0.77	54	7.2
#3: $\delta T_e \neq 0$ $\kappa_{ e} \neq 0$	0.58	5.8	1.0	0.17	0.72	0.2
#4: $\delta T_e \neq 0$ $\kappa_{ e} \neq 0$ & $\tilde{\mathbf{b}} \cdot \nabla$	0.9	11	2.8	0.38	3.6	0.8
DIII-D #119919 probe data	2.0	10	11.0	$\sim 0.15\text{-}0.2 \pm$	1.2	$\sim 0.4 \pm$

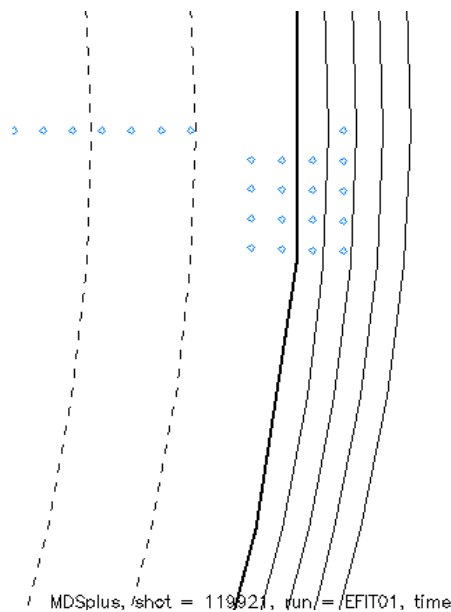
‡Typical, flux-surface-averaged values for L-mode discharges in DIII-D inferred from UEDGE

B. Cohen, et al., Int'l Sherwood 2012

BES Measurements: Long-Wavelength Density Fluctuation Characteristics in 119921-- G. McKee, Z. Yan

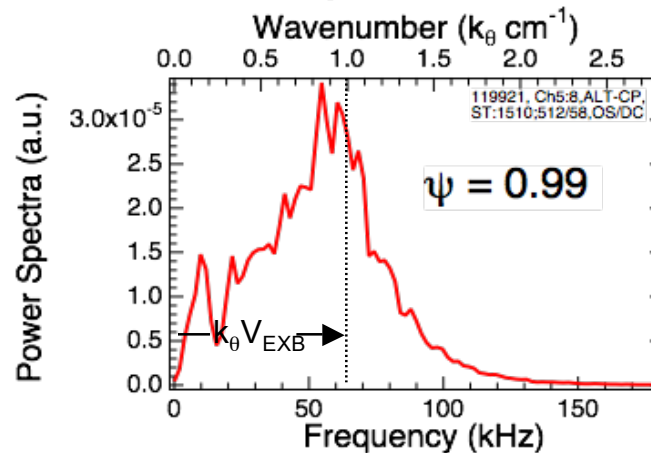
- Short beam-blips injected to obtain BES data during L-mode plasma conditions

BES 4x4 Grid



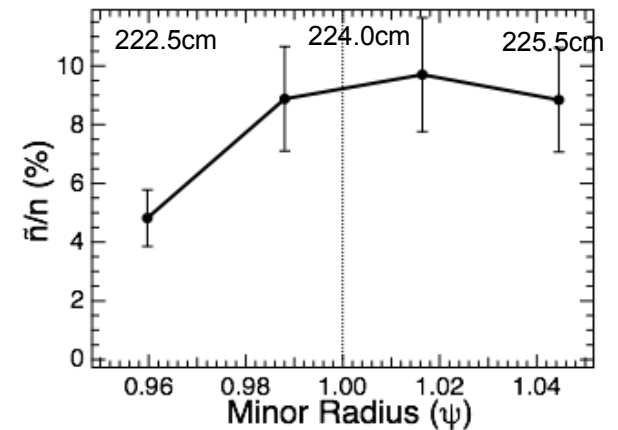
B. Cohen, et al., Int'l Sherwood 2012

Density Fluctuation Spectrum

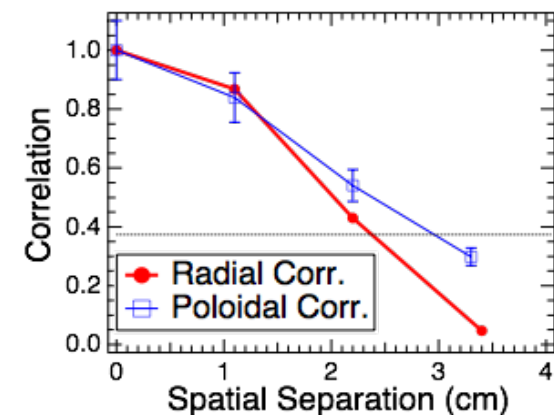


(Preliminary Analysis)

\tilde{n}/n Amplitude Profile



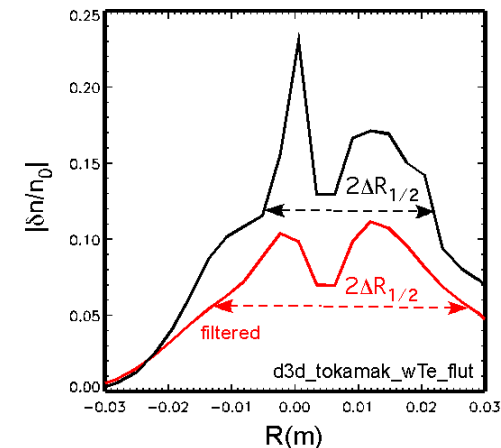
Spatial Correlation



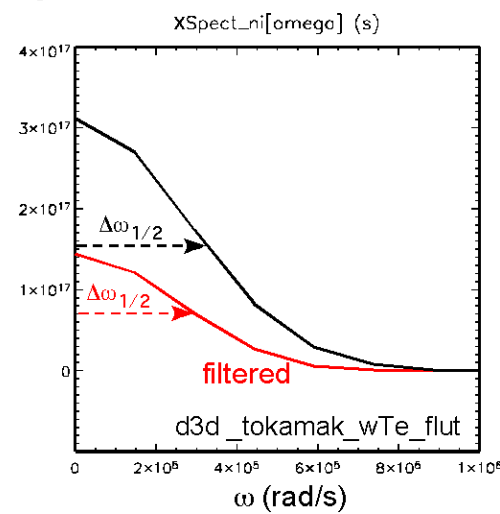
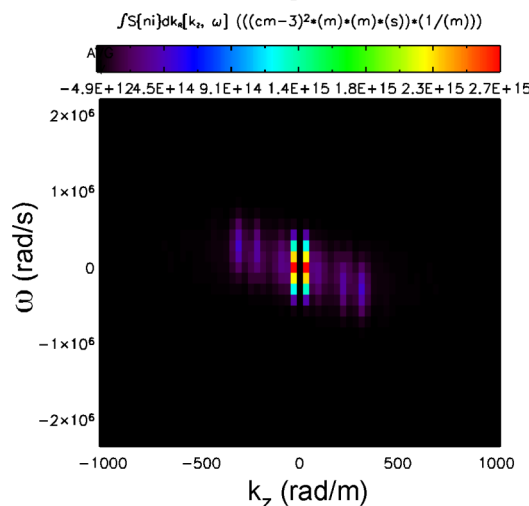
Synthetic Simulation Diagnostics Using GKV Suite to Match BES Data in Shot #119921

- We construct synthetic diagnostics using GKV suite of IDL routines to compare to BES data. **Spatial filtering** (1D or 2D) corresponds to 1 cm limit on spatial resolution in the BES grid in R and Z.
- $\langle E_r \rangle = 0$ in simulations, but $\langle E_r \rangle$ is finite in #119921 leading to Doppler shift in frequency $k_z V_{ExB}$ with $V_{ExB} = 3.9 \times 10^5 \text{ cm/s}$

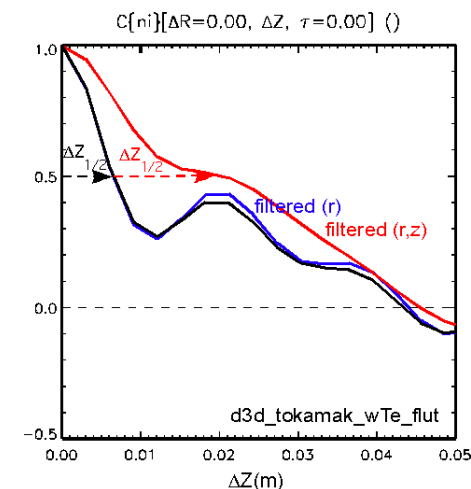
n/\tilde{n} Amplitude Profile in BOUT



Density Fluctuation Spectrum in BOUT

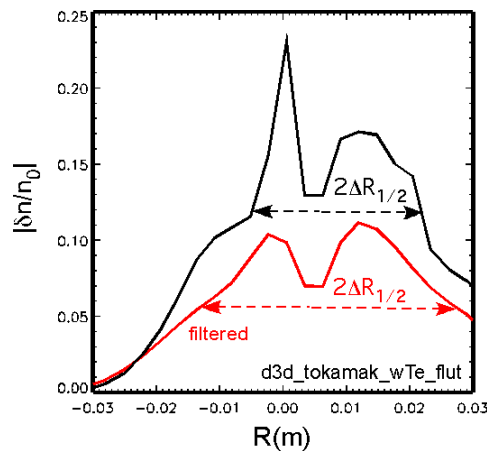


Spatial Correlation in BOUT

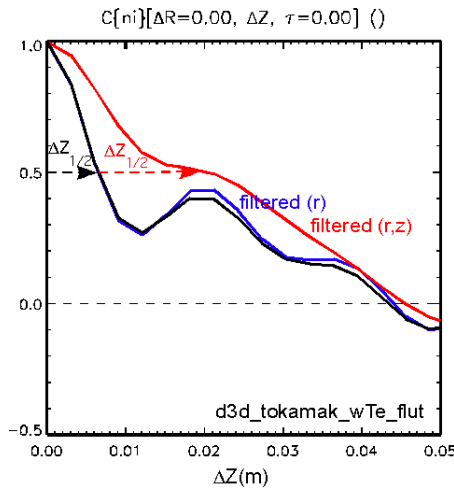


Comparison of Synthetic Simulation Diagnostics Using GKV Suite to BES Data in Shot #119921

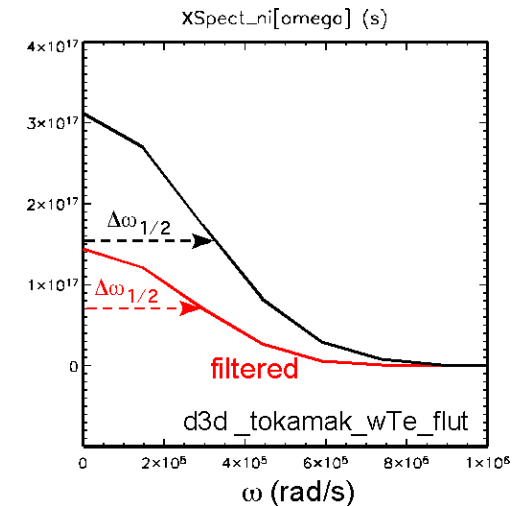
\tilde{n}/n Amplitude Profile



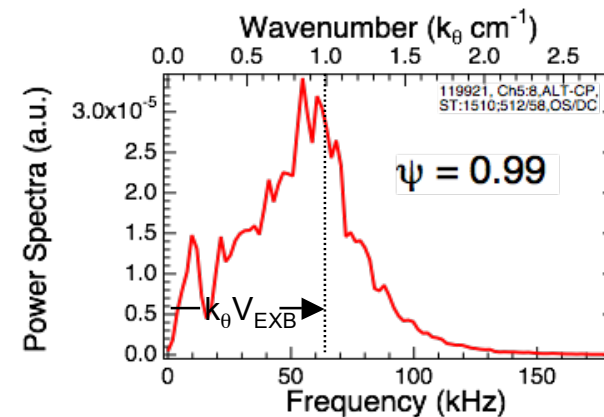
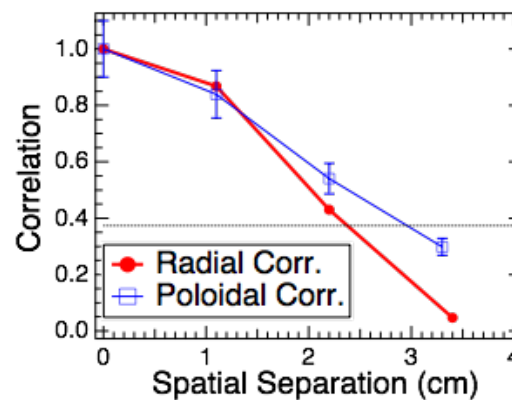
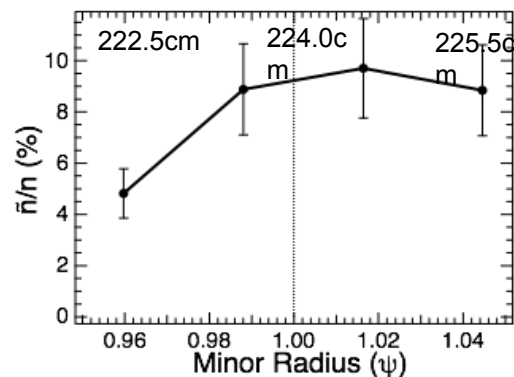
Spatial Correlation



Density Fluctuation Spectrum



BOUT



BES

Summary: Points of Agreement in Comparison of BOUT Results with BES Data as Physics Model Improves

- Comparison of suite of BOUT simulations to shot #119921 BES data: fluctuation frequency spectra, peak density amplitude radial half-width, correlation lengths
- Factor of 2 or better agreement seen between simulation **synthetic diagnostics with filtering** and the DIII-D #119921 BES data

Bout simulation	$\langle \delta N_i / N_i \rangle_{\text{rms}}$ peak vs. R raw/ filtered	$\Delta R_{\text{half-max}}$ of $\langle \delta N_i / N_i \rangle_{\text{rms}}$ (cm) raw/ filtered	$\Delta Z_{\text{corr, half-max}}$ of density (cm) raw/ filtered	Peak freq in density fluct'n spect, raw/ filtered (10^5 rad/s)	Freq half-max in density fluct'n spect, raw/ filtered (10^5 rad/s)
#1: $\delta T_e = 0$	0.13 / 0.07	1.2 / 1.5	0.6 / 0.9	3 / 0.5	4 / 2
#2: $\delta T_e \neq 0$ $\kappa_{\parallel e} = 0$	0.25 / 0.12	1.1 / 1.2	0.5 / 1.2	0 / 0	1.5 / 1
#3: $\delta T_e \neq 0$ $\kappa_{\parallel e} \neq 0$	0.17 / 0.08	1.7 / 1.9	0.4 / 1.4	0 / 0	1.5 / 1
#4: $\delta T_e \neq 0$ $\kappa_{\parallel e} \neq 0$ & $\tilde{\mathbf{b}} \cdot \nabla$	0.23 / 0.11	1.4 / 2.1	0.8 / 2	0 / 0	3.5 / 3
DIII-D #119921 BES data	0.09 \pm 0.2	2 \pm 0.2	2 \pm 0.2	3.8-$k_z V_{\text{ExB}}$ = -0.1 \pm 0.4 (Doppler shifted)	1.3 \pm 0.2